Efficiency Gains from Information and Communication Technology: A Spatial Analysis of Firm Geographic Expansion *

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Abstract

This paper studies a novel source of efficiency gains from information and communication technology (ICT): ICT widens firms' geographic span of control by reducing their internal communication costs. Using confidential US Census data, I document that firms with more advanced technology have both higher within-firm communication and larger geographic coverage. Using a quantitative spatial equilibrium model in which firms endogenously adopt ICT, choose multiple production locations, and trade domestically, I illustrate that multi-unit production is crucial in shaping the geographic distribution of efficiency gains from ICT improvement. I validate the model by exploiting natural experimental variation from the Internet privatization of the early 1990s. I estimate that privatization led to an 8.5% increase in the number of establishments per firm. Accounting for the effects of ICT on within-firm communication and establishment location, the model quantifies that privatization led to an overall efficiency gain of 1.3%. Finally, due to spillovers through multi-unit firms, the model shows that coordinated policies across locations have larger effects on local efficiency than uncoordinated policies.

JEL Codes: D24, F12, O33, R30, L23

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1 Introduction

Information and communication technology (ICT) has experienced dramatic improvements over the past three decades. Both governments and firms have made significant investments in ICT infrastructure on the premise that ICT produces sizable benefits. This paper proposes a novel source of efficiency gains from ICT: firms' geographic expansion. I show empirically and quantitatively that by improving within-firm communication for multi-unit firms, ICT widens the geographic span of control for firms that operate in multiple locations. Understanding their location choices in response to ICT improvements is crucial to assessing the aggregate and geographic implications of ICT development and policies.

My empirical analysis leverages confidential US Census data at the establishment level that provide rich information on both the firms' geographic footprints and their ICT adoption. As shown in Figure 1, US multi-unit firms have experienced significant expansion since the 1980s, and this growth was especially large during the mid-1990s and early 2000s when ICT—especially Internet-enabled technology—underwent rapid development. Using Census surveys of Computer Network Use, I show that firms that adopt advanced ICT are more likely to communicate within the firm and expand geographically.

To quantify the importance of firms' geographic expansion in enhancing efficiency, I develop and estimate a spatial equilibrium model of heterogeneous firms, in which firms endogenously adopt ICT, choose multiple production locations, and trade domestically. ICT lowers firms' internal communication costs between headquarters and production sites, allowing firms to expand and locate closer to markets. Through this geographic expansion, local ICT improvements affect not only the production efficiency of local establishments but also the multi-unit firms' establishments that are located elsewhere, thus impacting the efficiency of other locations. Compared to a trade-only model, the benchmark model predicts that efficiency gains from ICT are larger and more geographically dispersed.

I establish these results in five steps. In the first step, I leverage a confidential US Census dataset with establishment-level ownership linkages and geographic locations and augment it with data on the establishment's ICT adoption to document two motivating facts. First, firms that have adopted an *intranet*, which reduces firms' internal communication costs, experience larger growth rates in their geographic span of control. Second, intranet adoption increases the likelihood of within-firm communication using online networks, which further corroborates the role of declining internal communication costs in firms' geographic expansion.

Motivated by the empirical facts, in the second step, I propose a spatial equilibrium model of firm ICT adoption and location choices. In the model, firms choose a set of locations to open establishments but communicating among their establishments is costly. Firms can adopt advanced ICT to improve firm-wide effective productivity and to reduce communication costs between headquarters and establishments. ICT adoption and geographic expansion are complements: the benefit

of expanding to more locations is higher if a firm adopts ICT; the benefit of adopting ICT is also higher for a firm with a larger number of establishments. In equilibrium, reducing the cost of ICT affects firms' geographic span of control through two channels. On the one hand, firms' likelihood of adopting ICT rises, which increases the benefit of having a larger set of production sites due to the complementarity. Through this direct channel, the ICT cost reduction facilitates firms' geographic expansion. On the other hand, markets become more competitive as a larger fraction of firms improve efficiency by adopting ICT. This equilibrium channel mitigates geographic expansion.

The model clarifies the channels through which ICT improves efficiency. Absent multi-unit production, firms' production at their headquarters enhances efficiency through local production and the traditional trade channel. The option of setting up additional establishments generates new channels of efficiency gains: Firms' nonheadquarters establishments impact other locations' efficiency through trade via a third location and local production in the other locations, thus facilitating geographic spillovers of efficiency gains from ICT.

In the third step, I validate the model by exploiting quasi-experimental variation from one of the largest developments in US Internet history: the Internet privatization of 1995, a significant reduction in the costs of accessing high-speed Internet and adopting Internet-enabled applications. Privatization of the first high-speed Internet backbone—the National Science Foundation Network (NSFNET)—allowed commercial use of the backbone and catalyzed the Internet gold rush. Drastic improvements in almost all aspects of ICT followed.[1] I measure a firm's exposure to the Internet privatization by the distance from the firm's headquarters to the nearest Internet backbone node.[2] At locations closer to the nodes, infrastructure such as underground cables was more developed so that nearby firms were able to quickly benefit from the privatization.[3] Using a difference-in-differences approach, I find that the privatization increased the average number of establishments per firm by 8.5%. Particularly, the effect on multi-unit firms is equivalent to half of the overall increase after the privatization.

The key identification assumption is that absent the privatization, firms would have had the same trend in their geographic span of control regardless of distance to the NSFNET node. I justify this assumption with four pieces of evidence. First, graphical examination shows that parallel trends hold for firms headquartered at different distances to the nodes. Second, the

[1]The timing of these explosive developments, however, was unexpected. As described in Greenstein (2015), it was difficult for contemporaneous observers to predict the effects of the Internet privatization. Given the unprecedented scale of the initiative, companies adopted a "wait-and-see" approach and delayed taking significant action in the early 1990s. The Internet gold rush did not happen until the NSF finished its privatization plan. The history of Internet commercialization in the United States, including the deployment of Internet infrastructure, is reviewed and discussed in Greenstein (2015, 2020).

[2]The locations of Internet backbone nodes reflected historical contingencies regarding military concerns and proximity to research institutes.

[3]As the construction and installation of circuits is one of Internet service providers' major costs, Internet access would be cheaper for locations with better infrastructure.

estimates are robust across different specifications, such as those including controls for time-varying county characteristics and state–year and industry–year fixed effects. Third, I estimate the generalized propensity score of treatment and apply the inverse propensity score method to reweight the regression so that firms located at different distances are balanced on both firm and county characteristics. Finally, results are robust even if we leave out the "hot spots" surrounding NSFNET nodes. These sets of evidence offer reassurance that the baseline estimates are robust and reflect the effect of the Internet privatization.

In the fourth step, I exploit the exogenous variation from the reduced-form analysis and estimate the spatial equilibrium model for quantitative analysis. Key parameters concern the extent to which ICT reduces communication costs between firms' headquarters and establishments and to which it improves firm-wide effective productivity. I first quantify the effect of ICT on within-firm communication costs, which rise in the distance to headquarters, by estimating a model-derived within-firm gravity equation using establishment-level data. To account for the potential endogeneity of firms' ICT adoption, I use their distance to Internet backbone nodes as an instrument. Then, I estimate the effect of ICT on firm productivity, as well as the fixed costs of adopting ICT and setting up establishments, via the method of simulated moments (MSM). The main computation challenge is to calculate firms' optimal sets of locations, as combinations of locations increase drastically as the number of locations rises. I address this challenge by applying the algorithm proposed in Arkolakis et al. (2021). The estimation results show that within-firm communication costs increase with distance, although at a lower rate than trade costs. Adoption of advanced ICT reduces the elasticity of communication costs with respect to distance by 50% and improves firm productivity by 30%. The fixed costs of adopting ICT are estimated at US$1.16–1.45 million, lower than the costs of setting up establishments that range from US$2.37 to US$4.57 million.

In the last step, I use the estimated model to quantify the efficiency gains from ICT policies. I start by the Internet privatization that is studied in the reduced-form analysis. I simulate this reform by lowering the cost of ICT adoption so that the model-implied change in the number of locations per firm matches the reduced-form estimate. Overall, the Internet privatization increased efficiency by 1.3% on aggregate. Local efficiency increased between 0.9% to 1.5% across locations. The majority of these gains are accounted for by outside firms (i.e., firms headquartered in another location) and their entry and exit into the location. In contrast, local firms (i.e., firms headquartered in the location) account for less than one-fifth of local efficiency gains. The significance of outside firms in shaping local efficiency emphasizes that regions are interconnected and that ICT improvements can spill over across locations through multi-unit firms.

I illustrate that this cross-region interdependency through multi-unit firms is important for implementing policies that promote ICT access. Particularly, I compare two policies: 1) a coordinated national policy that universally reduces ICT costs for all locations, and 2) a set of uncoordinated local policies, each reducing ICT costs for one location with the others held unchanged. Given the same ICT cost reduction, I find that the coordinated policy yields over 4 times

larger efficiency gains than total gains from the uncoordinated policies. This difference is driven by spillovers through multi-unit firms: in a trade-only model, in which I shut down multi-unit production, the two policies increase efficiency by similar magnitudes.

Governments worldwide have spent billions on ICT infrastructure initiatives. For instance, the recent US infrastructure bill—the Infrastructure Investment and Jobs Act—includes programs promoting universal Internet penetration to reduce uneven Internet access. My results underscore that gains from ICT improvements differ across geographic locations and that it is important to understand how firm responses in relation to ICT adoption and geographic organization shape the gains from communication infrastructure development.

Relation to Literature. This paper improves our understanding of the gains from ICT improvements, a topic that has been extensively studied.[4] In closely related work, Bloom et al. (2014) use firm-level data and find a positive correlation between the firm span of control and the adoption of advanced ICT. Recent papers also document that ICT facilitates vertical fragmentation of production through phenomena such as outsourcing (e.g., Fort, 2017). Instead, this paper focuses on the impacts of ICT on firms' horizontal expansion across locations. I illustrate the mechanism in a model integrating firm ICT adoption with geographic expansion. I further use the estimated model to quantify the distribution of gains in improving ICT availability across locations in the United States.

This paper also complements the recent literature that studies differential effects of aggregate ICT cost reduction on local economic activities (e.g., Jiao and Tian, 2019; Rubinton, 2020; Eckert et al., 2020). To this end, I introduce multi-unit firms in a spatial equilibrium model. I show that the expansion of these firms and their location reoptimization are important in shaping the geographic distribution of economic activities.[5]

Firm expansion at the extensive margin has received increasing attention in the study of firm growth (e.g., Cao et al., 2019; Hsieh and Rossi-Hansberg, 2019; Aghion et al., 2019), and ICT has been a popular explanation for the extension of the firm's boundary. To the best of my knowledge, however, there is no existing evidence on the causal relationship between firms' ICT adoption and geographic span of control. This paper fills this gap by conducting a series of quantitative analyses, including exploiting exogenous variation from a natural experiment and model simulation exercises.

The model builds on a growing literature studying the geographic organization of firms that

[4] A long line of research has studied the implications of ICT for firm performance at the micro level and productivity growth at the macro level (e.g., Jorgenson, 2001; Jorgenson et al., 2003; Stiroh, 2002; Oliner and Sichel, 2000; Brynjolfsson and Yang, 1996; Brynjolfsson and Hitt, 1996, 2003; Dedrick et al., 2003; Aral et al., 2006; Van Reenen et al., 2007; Bloom et al., 2012; Baslandze, 2016; Lashkari et al., 2018). See Bresnahan (2010) and Goldfarb and Tucker (2019) for reviews of general purpose technology and recent development in digital economics.

[5] Giroud and Mueller (2019) and Giroud et al. (2021) show that local shocks can spill over across locations through multi-unit firms.

produce at multiple locations (e.g., Ramondo and Rodríguez-Clare, 2013; Tintelnot, 2017; Hu and Shi, 2019; Hsieh and Rossi-Hansberg, 2019; Oberfield et al., 2020; Gumpert et al., 2022). In particular, the paper builds and extends on Tintelnot (2017) by incorporating the endogenous communication cost through ICT adoption. A key challenge for computing the firm's optimal set of production locations arises from the combinatorial choice problem; i.e., the cardinality of the choice set is on the order of 2^N, where N is the number of potential production locations. On the computation end, the paper contributes by applying the algorithm proposed in Arkolakis et al. (2021) to solve the firm location choice problem and by integrating this algorithm into the estimation procedure and counterfactual exercises.[6]

Finally, the empirical strategy is related to the literature on the effects of ICT infrastructure that exploits the interaction between time variation in the arrival of technology and geographic variation in the proximity to technology (e.g., Forman et al., 2012; Falck et al., 2014; Akerman et al., 2015; Steinwender, 2018; Juhász and Steinwender, 2018; Hjort and Poulsen, 2019; Akerman et al., 2022; Hanlon et al., 2022). Most of the previous literature focuses on the effects on local market outcomes such as employment and firm behavior.[7] Through the lens of the model, this paper shows that in addition to direct effects on local markets, ICT improvements have distributional effects across locations.

Paper Outline. The rest of the paper is organized as follows. Section 2 describes the dataset sources and presents motivating facts. Section 3 develops the model. Section 4 discusses the 1995 Internet privatization and the reduced-form analysis. Section 5 conducts structural estimation, followed by simulation of the Internet privatization in Section 6 and alternative policy simulations in Section 7. Section 8 concludes.

2 Data and Empirical Motivation

ICT has been a popular explanation for the extension of the firm's boundary. Most related research, however, relies on aggregate data on ICT.[8] Rich microdata from the US Census provide a unique opportunity to investigate the firm-level relationship between firms' geographic expansion and their ICT adoption. In this section, I first describe the major data sources. Then, I show that ICT adoption can facilitate firms' geographic expansion by reducing within-firm communication costs.

[6] Jia (2008) develops an algorithm based on the lattice theory to solve WalMart's entry decisions. Antras et al. (2017) integrate the algorithm in estimation to study importers' sourcing choices.

[7] Notable exceptions include Steinwender (2018), who studies the effect of telegraph development in the 18th century in the United Kingdom on trade and finds significant efficiency gains.

[8] For instance, using aggregate IT price changes and industry-level productivity trends, Aghion et al. (2019) propose IT as a driving force that widens the firm's boundary, such as the number of establishments a firm operates, and thus leads to productivity slowdowns, declines in the labor share, and rising industry concentration.

2.1 Data Sources

One of the main datasets is the Longitudinal Business Database (LBD) from the US Census. It covers the universe of US establishments since 1976 and is updated annually. The LBD provides consistent identifiers at the establishment (LBDNUM) and firm (FIRMID) levels, which allows me to link establishments to their parent firms and track the firms over time. The data also record the establishment location's ZIP code, county, and state; employment; annual payroll; and industry codes constructed by Fort and Klimek (2018).[9]

I obtain information on ICT adoption from the Computer Network Use Supplement (CNUS) to the 1999 Annual Survey of Manufacturers (ASM). The key set of variables pertains to network adoption: the CNUS asks establishments whether they use the Internet, an intranet, a local area network (LAN), an electronic data interchange network (EDI), an extranet, or other networks. These network adoption variables are key to identifying different channels through which technology can facilitate firms' geographic expansion. For instance, an intranet—a private internal network that focuses on sharing information and smoothing communication among members inside the firm—reduces within-firm communication costs; an extranet—a private network that links the firm to its third parties such as customers and suppliers—expedites businesses with external parties. In addition to the network adoption items, the survey asks whether the establishment uses online networks (i.e., Internet, intranet, EDI, or extranet) to share information with other units in the company, external customers, or external suppliers.[10] I aggregate the establishments' ICT adoption and communication to the firm level, assuming that a firm has adopted certain networks and communicates with internal and external parties if one of the firm's establishments does so. My empirical results are robust to using alternative aggregation methods, such as taking averages across the firm's establishments.

Recent literature has documented that while the number of establishments a firm operates is increasing over time, the number of industries the firm covers is declining.[11] This indicates that firms' expansion is driven by their geographic expansion within industries, i.e., horizontal expansion. To focus on this within-industry expansion, I consider the establishments that a firm owns in each industry at the six-digit NAICS level. I do so by defining a firm by a FIRMID–industry pair.[12] Nonetheless, in the following empirical motivation, I show that firms' expansion

[9] I restrict the analysis to the contiguous US states; Alaska, Hawaii, Puerto Rico and the US Virgin Islands are excluded. As the industry classification system experienced a major change in 1997 and has been updated constantly, I use the consistent industry codes at the 6-digit NAICS level that are provided by Fort and Klimek (2018).

[10] The types of information include design specifications, product catalogs, demand projections, order statuses, production schedules, inventory data, and logistics and transportation information.

[11] Hsieh and Rossi-Hansberg (2019) documents that top firms in the US have reduced their sectoral coverage, reflecting increasing specialization. Ma (2022) shows that firms, particularly those engaging in R&D activities, have decreased their number of industries.

[12] The changes in the average number of establishments per firm, defined by a FIRMID-industry pair, equal the changes in the average number of establishments belonging to the same FIRMID, net of the changes in the average number of industries covered by a FIRMID. Appendix Section 9.2 provides details of the decomposition.

in all sectors and its relationship to technology adoption are qualitatively consistent with my baseline results.

I link firms' geographic span of control from the LBD with their network adoption from the 1999 CNUS to conduct firm-level analysis. As the CNUS data do not include nonmanufacturing firms, my main analysis focuses on the firms and their establishments in the manufacturing sector. Panel A of Table 1 reports summary statistics of the manufacturing firms in the LBD for the census years between 1977 and 2012, i.e., years ending in 7 or 2. There are 2,311,000 firm–year observations in the eight census years. Approximately 4% of these firms are multi-unit firms with more than one establishment.

Panel B of Table 1 reports summary statistics on firm ICT adoption, communication, and other firm characteristics of the CNUS sample. The variables regarding ICT delineate the state of technology adoption at the end of the twentieth century. The adoption rate of the basic Internet was high: 72.6% of firms were connected to the Internet in 1999, showing that the Internet was available to most businesses by then. LANs, which did not require Internet connections, also had a high adoption rate of approximately 64%. However, the adoption rate was low for advanced technologies such as intranets, EDIs, and extranets, which relied on high-speed Internet and sophisticated infrastructure.[13] In addition, approximately one-third of firms shared information inside the firm. A similar share of firms shared information with customers, while more firms—over half—shared information with their suppliers. Finally, 35.7% of firms in the CNUS sample are multi-unit, with 2.3 establishments on average. While the Annual Survey of Manufacturers tends to cover larger firms, particularly multi-unit firms, these firms have substantially enlarged their geographic span of control. Moreover, multi-unit firms account for a majority of US employment in the manufacturing sector, and thus an understanding of how ICT affects their geographic span of control can have important aggregate implications.[14] In some specifications in the reduced-form analysis, I apply the inverse propensity score to reweight observations so that firms included in the CNUS sample have similar characteristics, on average, to firms not included.

I use the number of establishments that a firm operates as the primary measure of the firm's geographic span of control. In robustness checks, I consider alternative measures that represent broader geographic scopes—such as the number of counties, states, and census divisions in which a firm has operations and the number of establishments at a nondrivable distance (i.e., further than 250 miles away) from the firm's headquarters or out of state.

Finally, I use the Census of Auxiliary Establishments (AUX) to obtain headquarters information for firms with stand-alone headquarters. The AUX is collected every five years, on years ending in 2 and 7, and covers nonproduction establishments of multi-unit firms such as their

[13]Forman et al. (2003) and Forman et al. (2012) use an alternative dataset, i.e., the Harte-Hanks Market Intelligence CI Technology database, and document similar patterns of a high adoption rate for the basic Internet but a relatively low rate for Internet-enabled applications that enhance business processes.

[14]Bernard and Jensen (2007) document that multi-unit firms account for 78% of employment and 88% of output in the manufacturing sector.

R&D centers and corporate headquarters. I augment the LBD with the AUX to identify firm headquarters' employment, payroll, and locations.[15]

2.2 Empirical Motivation

I present the firm-level correlation between the adoption of different networks and the firm's geographic expansion. An intranet, which reduces internal communication costs, turns out to be the most important network for a firm to adopt.[16] Then, leveraging variables from the CNUS data on firms' communication patterns, I provide evidence that corroborates the role of an intranet in facilitating within-firm communication.

2.2.1 Firms with ICT Adoption Experience Geographic Expansion

I measure the geographic expansion of a firm i around 1999 by its five-year growth rate in the number of establishments from 1997 to 2002 (i.e., $\Delta\widehat{\text{NumEstab}}_{i,97-02} = \log(\text{NumEstab}_{i,02}) - \log(\text{NumEstab}_{i,97})$) and correlate the growth rate with the firm's network adoption in 1999. I present the results in a regression framework:

$$\begin{aligned}\Delta\widehat{\text{NumEstab}}_{i,97-02} = \alpha &+ \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} \\ &+ \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,97}\gamma + \varepsilon_{i,97-02}, \end{aligned} \tag{1}$$

where the independent variables include indicators set to one if the firm installed an intranet, an EDI, an extranet, the Internet, or a LAN. To account for firms' initial conditions, I control for a vector of firm characteristics ($X_{i,97}$), including the logarithm of employment, firm age fixed effects, and state fixed effects at the beginning of the period in 1997. Since technology intensity may differ across industries, I include industry fixed effects at the four-digit NAICS level.

Panel A in Figure 2 plots the estimated coefficients for each type of network. Firms' network adoption—in particular, intranet adoption—is associated with a higher growth rate: having an intranet installed by 1999 is associated with a 3-percentage-point larger growth rate in a firm's number of establishments from 1997 to 2002. If we take into account that the average growth rate was 4.7 percentage points during this period, the estimated coefficient is equivalent to a 64% increase ($= 0.030/0.047 \times 100\%$). In comparison, the coefficient estimates for the other networks are statistically insignificant and economically small.

The baseline results rely on the sample of firms and their establishments in the manufacturing sector for which network adoption data are available. Recent literature shows a shift of employment from the US manufacturing sector to other sectors. For instance, Fort et al. (2018) document that

[15] Appendix 9.1 documents details of how I identify firm headquarters.

[16] Bloom et al. (2014) use intranet adoption, obtained from the Harte-Hanks Ci Technology database, as a proxy for the firm's internal communication costs.

incumbent manufacturing firms have increased their nonmanufacturing employment by adding new establishments. They show that electronic networks are positively correlated with firms' post-2000 growth in manufacturing employment and total employment in all sectors. Therefore, I also consider the firm's overall expansion across sectors. Panel B shows that firms that adopted online networks are associated with a higher growth rate in the total number of establishments in all sectors. In addition to intranet, the other networks also display positive coefficients, although the magnitudes of their coefficients are smaller or insignificant.[17]

Several caveats are worth noting. First, firms that plan to expand might have a higher incentive to adopt an intranet, leading to reverse causality. In Section 4, I exploit plausibly exogenous variation in firms' ICT adoption and show that firms experiencing larger ICT cost reduction are more likely to expand their geographic scope. Second, as the network adoption data are available only for 1999, it is possible that firms adopted these networks after 1999. If so, my estimate may be considered a lower bound.

2.2.2 ICT Adoption Facilitates Within-Firm Communication

To further corroborate the role of intranets in facilitating within-firm communication, I leverage variables from the 1999 CNUS data on firms' communication patterns. Particularly, I estimate the following regression:

$$\begin{aligned}\text{Communication}_{i,99} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} \\ + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,99}\gamma + \varepsilon_{i,99},\end{aligned} \tag{2}$$

where the dependent variable is an indicator set to one if any establishment of firm i shares information with other company units. The independent variables are the same as in Equation (1) and represent firms' network adoption. Taking advantage of the rich data from the ASM, I am able to control for a wider set of firm characteristics, including the logarithm of employment, the logarithm of the capital-to-labor ratio, and the skill mix, measured by the ratio of nonproduction workers to production workers. I also include state and industry fixed effects.

Panel C in Figure 2 confirms that firms with intranets are more likely to communicate within the firm and that intranets are the most important type of network for within-firm communication. The estimated coefficient on intranet adoption is over two times larger than that on other network adoptions.

As this regression exploits cross-sectional variation, one may be concerned that a firm's intranet

[17]Panel A in Appendix Figure 12 uses the growth rate in firms' total employment in all sectors as a dependent variable, which indicates that firms with advanced networks are associated with a higher growth rate. Another question is whether firms that adopted networks disproportionately expand in (non)manufacturing. As shown in Appendix Figure 12 Panel B, while most network adoptions are associated with larger growth rates in the firm's manufacturing employment share, the coefficients are statistically insignificant, reflecting firms' expansion in both the manufacturing and other sectors.

adoption is correlated with unobserved firm characteristics. Although estimations of communication outcomes are less likely to suffer from endogeneity issues than estimates of firm size and performance effects, I show that intranet adoption matters less for firms' external communication. If the result for within-firm communication is driven by unobservables that are positively correlated with intranet adoption, the estimate of the effect of intranet adoption on external communication is likely to be upward biased as well. Panel B in Figure 2 reports the results. The dependent variables corresponding to the circles and triangles are indicators set to one if a firm communicates with external customers and suppliers, respectively. Extranet adoption is the most important network for customer communication and Internet adoption for supplier communication. It is reassuring that intranets play a relatively small role in firms' communication with external parties, suggesting that their large effect on internal communication—and geographic expansion—is not merely driven by unobserved firm characteristics.

Overall, the firm-level evidence shows that reducing within-firm communication costs is one important channel through which ICT development facilitates firms' geographic expansion. In the following section, I incorporate these empirical findings with a structural model to provide a framework to quantify the efficiency gains from ICT improvements in equilibrium.

3 A Spatial Equilibrium Model with Multi-Unit Firms and ICT Adoption

I incorporate endogenous within-firm communication costs into an industry equilibrium trade model where firms can produce products in multiple locations (Tintelnot, 2017). I do so by allowing firms to adopt advanced ICT that lowers communication costs between the headquarters and production sites. I show that ICT adoption plays a nontrivial role in the firm's location choice. Moreover, multi-unit firms and their reoptimization of geographic footprints are important channels that shape the geographic distribution of efficiency gains from ICT improvement.

The economy consists of N locations, denoted by $\mathscr{N} = \{1, 2, \cdots, N\}$. In the following, I use "location" and "market" interchangeably. Each location $s \in \mathscr{N}$ is inhabited by a representative consumer and a continuum of firms born in location $i \in [0, m_s]$, where m_s is the exogenous mass of the firms in location s. The representative consumer sells labor in a perfectly competitive market and maximizes a CES utility function. The settings on firms follow those in Tintelnot (2017), assuming that each firm i produces a continuum of differentiated varieties $\omega \in [0, 1]$ that are tradable across locations. Each product is then indexed by a firm–variety combination (i, ω). Firms compete monopolistically in each product market.

I refer to a firm's birth location as its "headquarters" and denote it by o. The firm's additional establishment locations are denoted by s. Destination markets are denoted by k.

3.1 Demand

All varieties produced by firms are available to all markets. The representative consumer in each market k maximizes a CES utility function aggregating all varieties with elasticity of substitution σ:[18]

$$U_k = \left(\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}} d\omega di \right)^{\frac{\sigma}{\sigma-1}}, \tag{3}$$

where $y_{ok}(i,\omega)$ is the output of variety ω shipped to market k by firm i, which is headquartered at o. Given prices and the consumer's expenditure on manufacturing goods E_k, we can solve the consumer's problem and obtain demand from market k for firm i variety ω:

$$y_{ok}(i,\omega) = E_k P_k^{\sigma-1} p_{ok}(i,\omega)^{-\sigma}, \tag{4}$$

where P_k is the ideal price index of market k defined by

$$P_k = \left(\sum_{o=1}^{N} \int_0^{m_o} p_{ok}(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \text{ and where } \; p_{ok}(i) = \left(\int_0^1 p_{ok}(i,\omega)^{1-\sigma} d\omega \right)^{\frac{1}{1-\sigma}}. \tag{5}$$

The price index $p_{ok}(i)$ is firm specific and summarizes the prices charged to market k of all varieties produced by firm i, which is headquartered at o. The local price index P_k summarizes the prices charged to market k by all firms in the economy.

3.2 Production Technology

Each firm is endowed with an establishment in its birth location, called the headquarters, and can set up additional establishments in other locations with up to one establishment in each location. Production takes place in establishments. The value-added production function is Cobb–Douglas and has constant returns to scale. Productivity includes two components: firm-specific productivity (z_i), which affects all the firm's establishments and is independently and identically distributed across firms, and establishment-specific productivity (ε_{is}), which is drawn from a location-specific distribution $F_s(\varepsilon)$ and is independently and identically distributed across establishments in location s. Following Eaton and Kortum (2002), I assume that ε_{is} follows the Fréchet distribution with shape parameter θ and scale parameter T_s; that is, $F_s(\epsilon) = \exp(-(\epsilon/T_s)^{-\theta})$. The scale parameter T_s determines the state of technology in location s, and the shape parameter θ determines the dispersion of establishment productivity draws. Labor is the only input.

[18] Here, I assume that the elasticity of substitution is identical among varieties within and across firms. Antràs et al. (2022) relax this assumption and allow the elasticity of substitution within a firm to be different from that across firms.

Communication costs and ICT. Production in any establishment, including the headquarters, incurs an iceberg-type communication cost γ_{ios}: producing one unit of output requires γ_{ios} units of labor.[19] Guided by the empirical evidence that ICT helps firms expand by facilitating internal communication, I assume that communication costs vary with the firm's ICT adoption. Let φ_i denote firm i's ICT level. Consistent with the fact that the data contain firms' binary network adoption choices, I discretize φ_i into two levels—low and high, i.e., $\varphi_i \in \{\underline{\varphi}, \overline{\varphi}\}$. Firms that adopt a high ICT level are associated with low communication costs. In the following, I work with simple yet flexible communication technology, in which I decompose the communication cost into two terms:

$$\gamma_{ios} = \gamma_{os}(\varphi_i) = \underbrace{d_{os}(\varphi_i)}_{\text{HQ-establishment}} \quad \underbrace{h(\varphi_i)}_{\text{firm-wide}} . \tag{6}$$

Both terms depend on the firm's ICT adoption. The first term captures the communication costs due to remote production and is specific to the firm headquarters–establishment location pair. For instance, establishments farther from the headquarters may incur higher communication costs. Firms with a high ICT level have lower communication costs for any location pair, i.e., $d_{os}(\underline{\varphi}) \geq d_{os}(\overline{\varphi}) \geq 1$. I normalize the remote communication costs to one for local production, i.e., $d_{oo}(\varphi) = 1, \varphi \in \{\overline{\varphi}, \underline{\varphi}\}$. As is common in the literature, the second term reflects the firm-wide communication cost and can be viewed as a firm productivity shifter. Technologies such as intranets may improve the firm's overall management practice and reduce firm-wide communication costs. This term also decreases in the firm's ICT level, i.e., $h(\underline{\varphi}) \geq h(\overline{\varphi}) \geq 1$. Later in the estimation, I separately identify the impact of ICT on firms' production efficiency through these two channels.

Variable costs. The unit cost of firm i producing a variety ω at an establishment in location s and shipping it to market k is:

$$c_{iosk}(\omega) = \underbrace{(z_i/h(\varphi_i))^{-1}}_{\substack{\text{firm effective}\\ \text{productivity}}} \underbrace{(\varepsilon_{is}(\omega))^{-1}}_{\substack{\text{local}\\ \text{productivity}}} \underbrace{w_s}_{\substack{\text{input}\\ \text{cost}}} \underbrace{\tau_{sk}}_{\substack{\text{shipping}\\ \text{cost}}} \underbrace{d_{os}(\varphi_i)}_{\substack{\text{communication}\\ \text{cost}}} , \tag{7}$$

which summarizes the firms' effective productivity, local productivity, local input costs, shipping costs to the destination market, and communication costs between the production establishment and the headquarters. Adopting better ICT reduces variable production costs by increasing firm-wide productivity and, importantly, by reducing the cost of communication from the headquarters to establishments, which varies across location pairs.

Fixed costs. Firms are subject to a fixed cost f^X_{ios} when they set up another establishment in

[19] Within-firm physical shipping costs among establishments can be reflected in the same form of production loss. That said, Atalay et al. (2014) uses US Census data and finds that interplant shipping is rare. Moreover, I focus on the firm's within-industry expansion, which limits the scope for shipping of intermediate inputs within the firm.

addition to their headquarters. This fixed cost depends on the pair of locations of the headquarters and the establishment. For instance, firms are more likely to expand to closer locations because of easier access. Additionally, firms pay a fixed cost if they choose to adopt a high ICT level, and the cost can vary across firm headquarters locations, denoted by f_{io}^{ICT}. Both types of fixed costs are firm specific because the expansion decisions and ICT adoption can vary across firms with similar characteristics. As the fixed costs and their forms are unobservable from data, I assume that both types of fixed costs are paid in the numeraire with the same price across locations.

3.3 The Firm's Optimization Problem

Firms decide whether to adopt a high ICT level, choose optimal sets of locations for production, hire labor, produce a continuum of varieties, and serve destination markets. I use backward induction to solve the firm's optimization problem. I first derive the firm's optimal profit conditional on a set of establishment locations and ICT status. Then, I solve the firm's optimal choice of the set of locations and ICT adoption decision. To ease notation, from now on, I index firms headquartered at o by their productivity z and ICT level φ.

3.3.1 Production Given a Set of Establishment Locations and States of ICT

Let the set of locations $S \in \mathscr{S}$ be fixed. For each variety $\omega \in [0,1]$ and each market k, the firm chooses one of its establishments $s \in S$ that has the lowest unit cost $c_{osk}(\omega, \varphi, z)$ to serve the market. Thanks to the properties of the Fréchet distribution for establishment-specific productivity, we can define the firm's "production potential" of serving market k as

$$\Phi_{ok}(S, \varphi) = \sum_{s \in S} (T_s / w_s)^{\theta} (d_{os}(\varphi) \tau_{sk})^{-\theta}. \tag{8}$$

The production potential summarizes the states of technology (T_s) and wages (w_s) of all the firm's establishments, the shipping costs to market k from these establishments (τ_{sk}), and communication costs to the headquarters, which are endogenous to the firm's ICT level ($d_{os}(\varphi)$). Production potential increases in the firm's set of locations (S) and in the ICT level (φ). In particular, adopting better ICT improves the firm's production potential by reducing communication costs from the firm's headquarters to all its establishments. The exact increase, however, depends on the firm's headquarters, the set of establishment locations, and the proximity to the market, allowing for rich interaction between ICT adoption and the firm's internal geography.

Then, we can derive the firm's profit from market k given the CES demand:

$$\pi_{ok}(S, \varphi, z) = \frac{\sigma^{-\sigma}}{(\sigma - 1)^{1-\sigma}} \tilde{\Gamma} \left(\frac{z}{h(\varphi)} \right)^{\sigma - 1} E_k P_k^{\sigma - 1} \Phi_{ok}(S, \varphi)^{\frac{\sigma - 1}{\theta}}, \tag{9}$$

where σ is the elasticity of substitution across varieties, $\tilde{\Gamma} = \Gamma\left(\frac{\theta-\sigma+1}{\theta}\right)$ is a constant, and E_k and P_k are the consumer's total spending on manufacturing goods and the ideal price index in location k, respectively.[20] ICT adoption increases profits through 1) increasing the firm's effective productivity, which is represented by $z/h(\varphi)$, and 2) improving its production potential $\Phi_{ok}(S,\varphi)$ by reducing internal communication costs.

ICT and within-firm sales distribution. With the set of locations S held constant, ICT adoption affects the sales shares across the firm's establishments by changing the headquarters–establishment communication costs, i.e., $d_{os}(\varphi)$. Specifically, better ICT allows nonheadquarters and distant establishments to gain larger sales shares.

To see this, it is worth noting that the sales share of the establishment in location $s \in S$ relative to the firm's total sales to market k equals the establishment's contribution to the production potential of serving that market: $\zeta_{ok\leftarrow s}(S,\varphi) \equiv \text{sales}_{ok\leftarrow s}(S,\varphi)/\text{sales}_{ok}(S,\varphi) = \frac{(T_s/w_s)^\theta (d_{os}(\varphi)\tau_{sk})^{-\theta}}{\Phi_{ok}(S,\varphi)}$. Aggregating the sales across markets to the establishment level and normalizing by the sales at the headquarters, we obtain the following expression for normalized within-firm sales shares of an establishment in s for a firm headquartered in o with set of locations S and ICT level φ:

$$\begin{aligned}\log \tilde{\zeta}_{os}(S,\varphi) \equiv & \log \sum_k \zeta_{ok\leftarrow s}(S,\varphi) - \log \sum_k \zeta_{ok\leftarrow o}(S,\varphi) \\ = & -\theta \log d_{os}(\varphi) + \log\left(\sum_k \omega_{ok}(S,\varphi)\tau_{sk}^{-\theta} \Big/ \sum_k \omega_{ok}(S,\varphi)\tau_{ok}^{-\theta}\right) \\ & + \theta \log T_s/\log T_o - \theta \log w_s/w_o. \end{aligned} \tag{10}$$

The first term on the right-hand side indicates the location-pair communication cost between headquarters o and establishment s, which depends on the firm's ICT level φ. The second term represents the normalized establishment's market access, i.e., the average shipping costs from the establishment to all markets k, and is weighted by the corresponding market's demand, where the weight is $\omega_{ok(S,\varphi)} = \frac{E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1}\Phi_{ok'}(S,\varphi)^{\frac{\sigma-\theta-1}{\theta}}}$.[21] The last two terms represent the normalized local productivity and input cost at the establishment location s.[22]

Equation (10) resembles a *within-firm gravity equation* that links the establishment's sales share to an establishment location fixed effect, headquarters–set–ICT fixed effect, and the com-

[20] Appendix 11.2 provides more details on the derivation.

[21] Here, the market weights ($\omega_{ok}(S,\varphi)$) depend on the firm's ICT and geographic footprint via its production potential ($\Phi_{ok}(S,\varphi)$). $\omega_{ok}(S,\varphi)$ gives more weight to the market k to which the firm has smaller production potential, in comparison to the weight that considers only market demand, defined by $\tilde{\omega}_k = E_k P_k / \sum_{k'} E_{k'} P_{k'}$. For instance, a firm that is headquartered in the Pacific census division and has an additional establishment in New England places smaller weights on market demand from the Pacific, where the firm has relatively high production potential.

[22] Appendix 11.3 provides the derivation of Equation (10). Appendix 11.4 shows in a simple example with three locations that ICT adoption allows firms to allocate more sales to nonheadquarters and distant establishments.

munication costs between the two locations. Later in the estimation in Section 5, I use this insight to provide an estimation framework that exploits the within-firm shares to quantify the effect of ICT adoption on headquarters–establishment communication costs.

3.3.2 Optimal Set of Locations and ICT Adoption

Firms choose the optimal ICT level and the optimal set of locations to maximize their profits, net of fixed costs of expansion and ICT adoption. Specifically, the firm's problem is

$$\pi_o(z) = \max_{\varphi \in \{\underline{\varphi}, \overline{\varphi}\}} \left\{ \max_{S \in \mathscr{S}} \left(\sum_{k=1}^{N} \pi_{ok}(S, \varphi, z) - \sum_{s=1}^{N} \mathbb{1}[s \in S] f_{os}^{X} \right) - \mathbb{1}[\varphi = \overline{\varphi}] f_o^{ICT} \right\}, \tag{11}$$

where $\pi_{ok}(S, \varphi, z)$ is defined above in Equation (9).

Complementarity between ICT adoption and geographic expansion. A key feature of the model is that technological upgrading and geographical expansion complement each other. First, the benefit of expanding is larger for firms that have adopted better ICT. Consider a simple case with three locations and a single-unit firm deciding whether to expand its production to other locations. Let HQ denote the firm's headquarters location, L a nearby location with relatively low local productivity and a low fixed cost of setting up establishments, and H a faraway location that is more productive but also incurs a higher fixed cost. The firm has four combinations of establishment locations: keeping production local (i.e., $\{HQ\}$), expanding to one of the other locations (i.e., $\{HQ, H\}$ or $\{HQ, L\}$), and expanding to both locations (i.e., $\{HQ, H, L\}$). The firm compares the cost and benefits of each combination. For example, a firm would like to add an establishment at L if and only if the additional gross profit exceeds the fixed cost of setting up the establishment there:

$$\begin{aligned}
&\sum_{k=1}^{N} \pi_{ok}(\{HQ, L\}, \varphi, z) - \sum_{k=1}^{N} \pi_{ok}(\{HQ\}, \varphi, z) \\
&= \frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}} \tilde{\Gamma} \left(\frac{z}{h(\varphi)} \right)^{\sigma-1} \sum_{k} E_k P_k^{\sigma-1} \underbrace{\left((\Phi_{HQ,k}(\{HQ, L\}, \varphi))^{\frac{\sigma-1}{\theta}} - (\Phi_{HQ,k}(\{HQ\}, \varphi))^{\frac{\sigma-1}{\theta}} \right)}_{\text{Expansion increases production potential}} \geq f_{HQ,L}^{X}.
\end{aligned}$$

The left-hand side is the benefit of expanding to location L, i.e., the difference in gross profits by Equation (9); the right-hand side is the fixed cost of setting up an establishment at L for a firm headquartered at HQ. The benefit is positive because the production potential $\Phi_{ok}(S, \varphi)$ increases as firms set up more establishments. High ICT increases this benefit of geographic expansion through two channels. First and foremost, the difference in production potential is larger for firms with better ICT, as ICT improves the production efficiency of nonheadquarters establishments by

reducing the costs of communication with the headquarters.[23] Second, ICT increases the firm's effective productivity $\tilde{z} \equiv z/h(\varphi)$, which further raises the benefit of expanding.

Panel A in Figure 3 plots the policy function of the number of establishments against the firm fundamental productivity z, along with the exact set of locations S, to show how ICT impacts firm location choices. The black dotted line corresponds to the low ICT level. As firms need to pay fixed costs to build additional establishments, the policy function is a step function, and more productive firms can expand to more locations. It is noteworthy that the set of locations does not monotonically increase in productivity. In the middle range of productivity, firms display different expansion patterns, even though the number of establishments is the same: Relatively less productive firms expand to L, while more productive firms expand to H—a preferable location with higher local productivity that requires a higher fixed cost. The red solid line corresponds to the high ICT level. Given the same fundamental productivity, adopting better ICT not only increases the firm's effective productivity but also improves production potential to all markets, leading to an increase in the firm's likelihood of relocating from L to H or expanding to more locations.

Second, the benefit of adopting ICT is larger for firms with a larger set of locations. In particular, a firm would like to upgrade to high ICT if and only if the benefit exceeds the fixed cost of adopting ICT; that is,

$$\sum_{k=1}^{N}\pi_{ok}(S,\overline{\varphi},z)-\sum_{k=1}^{N}\pi_{ok}(S,\underline{\varphi},z)=\frac{\sigma^{-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma}\Bigg\{\underbrace{\left[\left(\frac{z}{h(\overline{\varphi})}\right)^{\sigma-1}-\left(\frac{z}{h(\underline{\varphi})}\right)^{\sigma-1}\right]\sum_{k=1}E_kP_k^{\sigma-1}\Phi_{HQ,k}(S,\overline{\varphi})^{\frac{\sigma-1}{\theta}}}_{\text{ICT adoption increases firm's effective productivity}}$$
$$+\underbrace{\left(\frac{z}{h(\underline{\varphi})}\right)^{\sigma-1}\sum_{k=1}E_kP_k^{\sigma-1}\left(\Phi_{HQ,k}(S,\overline{\varphi})^{\frac{\sigma-1}{\theta}}-\Phi_{HQ,k}(S,\underline{\varphi})^{\frac{\sigma-1}{\theta}}\right)}_{\text{ICT increases production potential}}\Bigg\}\geq f_{HQ}^{ICT}.$$

Both benefits of adopting ICT—increasing effective productivity and improving production potential—increase in the set of locations.[24] Therefore, all else held constant, firms with larger sets of locations are more likely to adopt ICT.

Panel B plots the joint decision of location choice and ICT adoption and demonstrates comple-

[23] In this case, denote the increase in production potential by $\Delta(\varphi) \equiv (\Phi_{HQ,k}(\{HQ,L\},\varphi))^{\frac{\sigma-1}{\theta}} - (\Phi_{HQ,k}(\{HQ\},\varphi))^{\frac{\sigma-1}{\theta}} = \left(T_{HQ}^{\theta}(w_{HQ}\tau_{HQ,k})^{-\theta}+T_L^{\theta}(w_L\tau_{L,k}d_{HQ,L}(\varphi))^{-\theta}\right)^{\frac{\sigma-1}{\theta}} - \left(T_{HQ}^{\theta}(w_{HQ}\tau_{HQ,k})^{-\theta}\right)^{\frac{\sigma-1}{\theta}}$, where $k \in \{HQ,L,H\}$. Since ICT reduces communication costs between the headquarters and establishments, i.e., $d_{HQ,L}(\overline{\varphi}) < d_{HQ,L}(\underline{\varphi})$, and $(\sigma-1)/\theta > 0$, we can obtain that the increase in production potential for any market is larger for a firm with better ICT.

[24] First, the production potential increases in the set of establishments S, so the benefit from higher effective productivity is larger following the firm's expansion. Second, the benefit from the increasing production potential is larger when a firm includes additional establishments. Take the same example in which a firm either produces locally with $S = \{HQ\}$ or expands to another location with $S = \{HQ, L\}$. The benefit from the production potential is zero for the former case but is strictly positive for the latter, as the communication costs decrease. Nonheadquarters establishments always benefit from lower communication costs with the headquarters.

mentarity between the two decisions. The fixed cost of adopting ICT further creates a cutoff above which firms find it profitable to upgrade to better technology. Less productive firms maintain low ICT and local production, while more productive firms adopt better ICT and further expand their geographic footprints.

3.4 Equilibrium

To fit manufacturing into the entire economy, I assume a nonmanufacturing sector selling homogeneous products that can be traded costlessly across locations. Consumers spend a constant fraction (η) of final expenditure (G_s) on manufacturing goods. Labor is freely mobile across the two sectors. The nonmanufacturing sector is large enough that the wage is pinned down by productivity in that sector and total income is exogenous.[25]

Let μ_o denote the exogenous measure of firms headquartered in location o and Z the support of firm productivity. The product market clearing condition is $\forall k = 1, \cdots, N$:

$$\eta G_k = P_k Y_k, \text{ where } P_k = \Big(\sum_{o=1}^{N} \int_Z p_{ok}(z)^{1-\sigma} d\mu_o(z) \Big)^{\frac{1}{1-\sigma}} \text{ and } Y_k = \Big(\sum_{o=1}^{N} \int_Z y_{ok}(z)^{\frac{\sigma-1}{\sigma}} d\mu_o(z) \Big)^{\frac{\sigma}{\sigma-1}},$$

where $p_{ok}(z)$ and $y_{ok}(z)$ are the price and sales, respectively, to market k from a firm headquartered in location o and with productivity z.

Equilibrium is a vector of prices $\boldsymbol{P}$ consistent with firm optimization and clears the product market for each location. The price indices affect total output not only through demand but also through firms' ICT choices and production location choices.

3.4.1 Equilibrium Effects of an ICT Cost Reduction

Due to technology and infrastructure improvements, the cost of ICT has decreased dramatically over the past decades. I analyze the equilibrium effects of an ICT cost reduction on a firm's location choices and on local efficiency. Decomposition of local efficiency shows that multi-unit production is important in determining the geographic distribution of efficiency gains.

Effects on firm's location choices. In equilibrium, an ICT cost reduction affects the firm's geographic span of control through two channels. As a direct effect, firms are more likely to adopt ICT, which leads to expansion due to complementarity between the two decisions. As an

[25] I assume that labor supply is perfectly elastic, and wages are treated as exogenous. Nevertheless, key mechanisms are still operative in endogenous labor markets regarding the equilibrium effects on firm expansion decisions. Consider the extreme case in which labor supply is perfectly inelastic. With endogenous labor markets, as the fixed cost decreases, labor demand increases, thus driving up wages. The production potential term $\Pi_{ok}(S, \varphi)$, which is a function of the inverse of wages, decreases. Price indexes decrease, and expenditure increases, with the two offsetting each other. The equilibrium effect, again, works as a countervailing force that reduces the appeal of geographic expansion.

indirect effect, markets become more competitive due to increasing firm efficiency, which leads to contraction. The relative strength of the direct and indirect effects determines the net changes in the firm's geographic span of control in equilibrium.

Figure 4 decomposes the equilibrium effects into direct and indirect effects in the three-location example. Panel A shows the direct effect, in which equilibrium prices are held constant. The solid line represents the policy function of ICT adoption and location choice when the ICT cost is high, which is the same as that in Panel B of Figure 3. The black fragment corresponds to the productivity range in which firms maintain a low ICT level, and the red fragment corresponds to firms that adopt better ICT. The dotted line represents the policy function with a lower ICT cost and with the prices held constant. As the ICT cost declines, all firms with midrange productivity, particularly those on the left end, can adopt better ICT. The cutoff between one and two establishments is shifted to the left, indicating an increase in the fraction of firms expanding from their headquarters to another location. The direct effect leads to expansion in the firm's geographic span of control.

Panel B adds a dashed line representing the policy function with a low ICT cost but allows equilibrium prices to adjust endogenously. The cutoff between two and three locations is shifted to the left: those firms on the margin, which always adopt better ICT, have to shrink their geographic coverage due to tougher competition. The cutoff between one and two locations is also shifted to the right in comparison to the case with fixed prices (i.e., the dotted line). Compared to the likelihood in the high ICT cost case (i.e., the solid line), however, the likelihood of expanding from headquarters to another location increases, driven by the direct effect.

Efficiency gains. Absent multi-unit production, local efficiency is determined by local production of firms headquartered in the location (i.e., local firms) and a traditional trade channel of firms headquartered in other locations (i.e., outside firms). With the option of multi-unit production, outside firms can set up establishments in the location, which directly affects local efficiency. Moreover, outside firms shape local efficiency through entry and exit into the location as they reorganize their geographic footprints. Finally, firms' nonheadquarters establishments can impact another location's efficiency through a third-location trade channel, which differs from the traditional trade channel that captures trade from firms' headquarters.

Below is a summary of the different channels through which local efficiency is affected.

- Channel 1: Local production by local firms
- Channel 2: Traditional trade by outside firms' headquarters production
- Channel 3: Multi-unit production:
  - (a) : Local production by outside firms
  - (b) : Entry and exit of outside firms

- Channel 4: Third-location trade by firms' nonheadquarters production

To highlight the role of multi-unit firms and their location choices in determining the geographic distribution of efficiency gains in equilibrium, in Appendix Section 11.5 I decompose local efficiency, reflected in the local price index P_s, into the contributions from different types of firms. The decomposition shows that, in addition to the efficiency gains from improving effective productivity (i.e., $z/h(\varphi(z))$) via channels 1 and 2, multi-unit firms facilitate the spread of efficiency gains via channels 3 and 4—both through the firms' existing establishments and through endogenous entry and exit when they reoptimize their geographic footprints.

4 Reduced-Form Evidence from Internet Privatization

In this section, I show that consistent with the model implication, improving ICT facilitates firms' geographic expansion. To do so, I exploit natural experimental variation from a milestone in early US Internet history—the Internet privatization. The explosive development in ICT, especially intranet technology, which facilitates internal communication, following the privatization allowed firms to widen their geographic span of control.

The goal of this section is twofold. First, the reduced-form analysis validates the model prediction. Second, it develops an instrument for firm ICT adoption that I use in Section 5 for structural estimation.

4.1 Internet Privatization

The development of the Internet has been a key part of the recent history of information and communication technology. From the time of early dial-up access to the broadband era, improvements to the Internet, including the provision of faster connection speeds and the development of various applications, have changed every aspect of business activities. Prior to 1995, the Internet was nothing like what it currently is. The foundation of today's Internet was NSFNET, the first high-speed Internet backbone in the US, launched in 1986 and operated by the government through the NSF. By the early 1990s, NSFNET connected sixteen node sites across the US. These node locations reflected historically contingent factors related to their proximity to military bases and university locations.[26] As shown in Figure 5, these nodes were located in Ithaca, Princeton, San Diego, Champaign, Boulder, and Lincoln, among other locations. Additionally, NSFNET utilized a three-tiered architecture. Each node was connected to regional networks, which were in turn linked to the backbone.

NSFNET was originally for the use of the research and higher education community, so its commercial use was restricted. Businesses were generally not allowed to connect to NSFNET to

[26]Several NSFNET node locations were inherited from the Advanced Research Projects Agency Network (ARPANET)—NSFNET's predecessor, a military-funded Internet backbone run by the Department of Defense.

carry their data. With exploding interest and demand from the commercial side, however, these restrictions were gradually lifted. Eventually, in the early 1990s, the Internet—once a government asset—was handed over to the private sector. Privatization of the Internet was finalized on April 30, 1995. Following privatization, the Internet gold rush started.[27] I exploit this historical event and use the privatization of NSFNET as a natural experiment.[28]

4.2 Reduced-Form Analysis

4.2.1 Empirical Approach

I use the distance from a firm's headquarters to the nearest NSFNET node site to measure the firm's exposure to the Internet privatization. Locations closer to these nodes had better infrastructure, such as underground fiber optic lines, which was crucial for Internet access. Businesses often access the Internet through leased lines, which requires physical lines near the companies. As the construction and installation of circuits is one major cost for Internet service providers, the costs of Internet access for businesses were lower if they were in locations with better infrastructure.[29] In addition, many NSFNET nodes were located on university campuses, where more talent was able to provide ICT services.[30]

My empirical approach builds on the idea that following the Internet privatization, firms located closer to Internet backbone nodes experienced a larger cost reduction in accessing high-speed Internet and thus advanced business applications, such as intranet technology. Although panel data on firms' ICT adoption are not available, I use firms' intranet adoption in the 1999 CNUS data to provide first-stage evidence. Since Internet-enabled applications such as intranets were invented after the privatization, their adoption rate in 1999 reflects the change in the likelihood of use of these technologies. I sort firms according to their distance to the nearest NSFNET node (in hundreds of miles), i.e., HQDistToNode, and calculate the fraction of firms that adopted an intranet in each distance quintile. To make locations and firms comparable along the distance, I control for county characteristics and include industry and state fixed effects. Figure 6 shows

[27]The conversation concerning the privatization of the Internet started from the early 1990s. In approximately 1992, policies that allowed commercial businesses to connect to the Internet were implemented. Nevertheless, the final privatization of the Internet in 1995 served as a catalyst of the Internet gold rush. Appendix Section 10.1 provides more details on the development and privatization of NSFNET.

[28]The slow-growing number of Internet service providers before 1995 and the market explosion shortly after 1995 reflect the critical role of the Internet privatization. This further justifies my empirical strategy, which uses this event as an exogenous shock to information and communication technology.

[29]McKnight and Bailey (1998) documented that costs for leased lines and routers accounted for 80% of total NSFNET costs. Bloom et al. (2014) use country-level variations in the leasing of telephone lines to instrument for firms' probability of adopting an intranet; they use the distance to the headquarters of SAP—a world leading enterprise resource planning (ERP) provider—to measure firms' probability of adopting ERP software. Forman et al. (2012) use county-level variation in the number of nodes for ARPANET—the predecessor of NSFNET—as an instrument for local advanced IT investment by businesses.

[30]Goldfarb (2006) shows that students enrolled in universities in the mid-1990s were more likely to use the Internet.

that firms located closer to nodes were more likely to have adopted an intranet in 1999 after the Internet privatization, indicating that the distance measure can capture heterogeneity in the effect of the Internet privatization on intranet adoption.

The reduced-form analysis takes the form of a difference-in-differences regression framework:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}, \tag{12}$$

where Y_{it} is a measure of the geographic span of control of firm i in year t, α_i is firm fixed effects, HQDistToNode_i is the distance (in hundreds of miles) of the ZIP code in which firm i is headquartered to the nearest NSFNET node, and Post_t is an indicator set to one for years from 1995 onward. The coefficient of interest is β, which reflects the impact of the Internet privatization on a firm's geographic span of control. Standard errors are clustered at the firm and county levels.

The degree of geographic expansion may differ across industries. For instance, industries with high trade costs added more establishments. To account for differential industry trends, I include industry–year fixed effects, where the industry is at the 4-digit NAICS level. I also include state–year fixed effects to ease the concern that the results are driven by differential expansion patterns across locations, e.g., due to state fiscal policies.

One may be concerned that firm growth may be correlated with local conditions. To control for potential local shocks that affect firms' expansion decisions, in some specifications, I include a set of county–year-specific characteristics, such as the logarithm of the population and median household income, the shares of the Black population and of people over 65 years old, and the share of adults with bachelor's degrees.

Estimation sample. Local infrastructure characteristics, such as Internet accessibility, can affect firms' location choices and thus their headquarters locations. Firms with expansion plans may choose to locate their headquarters in areas with better Internet infrastructure. To eliminate concerns regarding endogenous headquarters locations and abstract from firm entry and exit, I focus on a balanced panel of firms in the LBD from 1987 to 2007 for the main reduced-form analysis. The balanced sample includes approximately 33,500 firms and thus 702,000 firm–year observations for the twenty-one years from 1987 to 2007. Table 12 shows that firms in the balanced sample tend to be larger and are more likely to be multi-unit firms. An average firm in this sample has 1.34 establishments.

Graphical evidence. The key identification assumption is that the Internet privatization did not coincide with other location-by-year shocks, as the distance measure uses the firm's headquarters location. To validate this assumption, I first show graphical evidence that firms located close to nodes had a geographic span of control similar to that of firms located farther away. I show this by estimating the following regression, which allows the coefficient on the interaction term in

Equation (12) to vary for each year:

$$Y_{it} = \alpha_i + \beta_t \text{HQDistToNode}_i + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}. \tag{13}$$

Here, I use the number of establishments of firm i in year t to measure the firm's geographic span of control. The coefficients β_t measure the relationship between the firm's distance to the nearest NSFNET node and its number of establishments for each year both before and after the 1995 Internet privatization. Figure 7 plots the estimates of these coefficients. For easier presentation, I normalize the coefficients by the estimate in 1994, i.e., $\beta_t - \beta_{1994}$, and multiply them by -1. The coefficients are precisely estimated around zero for the period before the Internet privatization, indicating that firms with different distances to nodes had similar trends prior to the privatization. For years from 1995 onward, the estimated coefficients are negative (positive after multiplied by -1 in the graph), indicating that firms located *closer* to NSFNET nodes had *more* establishments.

Following the Internet privatization, the number of establishments gradually increased for firms headquartered closer to NSFNET nodes. The gradual increase in firms' footprints may reflect the time needed to integrate ICT systems into firm operations or set up new establishments. The estimates are statistically significant at the 5% level and stable over the 2000s, suggesting that the benefits for firms close to nodes were long-lasting, e.g., due to the constant arrival of new technologies or initial competitive advantages for firms expanding at an early stage.

4.2.2 Regression Results

Table 2 reports the estimates from the difference-in-differences regression in Equation (12), which quantifies the effect of the Internet privatization on firms' geographic span of control. The regressions are weighted by firm employment shares for the baseline results. Column (1) of Panel A shows that firms located closer to NSFNET nodes experienced larger expansion after the privatization. The coefficient on the interaction term between distance to the node and the postreform indicator is estimated at -0.328, indicating that firms located 100 miles *closer* to a node are associated with 0.328 *more* establishments after privatization. As the average distance is approximately 130 miles, the Internet privatization increased firms' geographic span of control, on average, by 0.426 ($= 0.328 \times 130/100$) establishments. Given the average of 5.016 establishments per firm, this translates into a $8.5\% = 0.426/5.016 \times 100$ increase. Column (2) includes time-varying county characteristics as additional controls. The point estimate is similar, which reassures us that the effect is not driven by shocks to local conditions such as local population or education levels.

Column (3) of Panel A restricts the estimation sample to multi-unit firms and yields an estimate of -0.442. Given an average number of establishments of 8.841, this estimate implies an increase of 6.5% ($= 0.442 \times 130/8.841$) for multi-unit firms. Another way to interpret the magnitude is to compare to the overall increase after the privatization. As shown in Panel B of Figure 10, the average number of establishments for multi-unit firms increased by approximately 12% during the

postprivatization period. That is, the increase attributable to the Internet privatization accounts for half of the overall increase in multi-unit firms' number of establishments. One caveat is that the effect implied by the difference-in-differences estimate is a partial equilibrium effect while the overall increase may reflect the general equilibrium effect. I further investigate the general equilibrium effect of the Internet privatization through the lens of a quantitative model in Section 5.

Robustness. One may be concerned that firms located closer to NSFNET nodes are different from those located far away and that locations near nodes might have larger populations or a higher education level. I construct generalized propensity scores of treatment, conditional on firm and county characteristics before the privatization, and apply the inverse propensity score method to reweight the observations (see Robins et al., 2000; Hirano and Imbens, 2004; Abadie, 2005).[31] This adjustment makes faraway firms similar to nearby firms. Figure 14 shows that after the propensity score reweighting, firm and county characteristics are balanced along the distance. Column (4) of Panel A in Table 2 shows that increase implied by the reweighted difference-in-differences estimate is similar to the baseline result.[32] As another robustness check to address the potential endogeneity of firms' headquarter locations, I test whether the effect of the Internet privatization differs for firms headquartered at different ranges of distance to NSFNET nodes. If these node locations were chosen for their proximity to "intellectual hubs" and nearby firms disproportionately benefited from privatization, we should see stronger effects at shorter distances. Appendix 10.3 shows that the estimated effects are larger, if anything, for firms headquartered far away from the nodes. Taken together, these results confirm that firms' initial selection into different locations is unlikely to drive the baseline difference-in-differences estimate.

Column (5) of Panel A in Table 2 shows estimates from the unweighted regression. The difference-in-differences coefficient is estimated at -0.044, equivalent to an increase of 4.3% ($= 0.044 \times 130/1.340$). The magnitude is approximately half that of the baseline estimate, where the regression is weighted by firm employment share, indicating that the privatization had larger impacts on large firms.

In addition, the estimated effects are robust to alternative measures of firms' geographic span of control as the dependent variable. In Panel B of Table 2, columns (1)–(3) report the estimation results for the number of counties, states, and census divisions in which a firm operates, respectively. The estimated coefficients are statistically significant and economically meaningful. The Internet privatization increased firms' geographic coverage by 7% at the county level, 5.5% at the state level, and 2.6% at the census division level. These results show that the baseline result is not driven by firms opening establishments in nearby locations but instead captures broad geographic expansion. Columns (4) and (5) consider the number of establishments outside the headquarters state and at a nondrivable distance (i.e., over 250 miles away) from the headquarters, respectively.

[31] Appendix 10.2 provides more details on how I construct these scores.

[32] The reweighted difference-in-differences estimate is 0.065. This estimate translates into a 7.2% increase in the firm's number of establishments, similar to the 8.5% increase from the baseline regression.

The estimated coefficients are similar to the baseline estimate, indicating that the increasing number of firm establishments is driven by those located far away from firms' headquarters.

Finally, Appendix Section 10.4 studies the intensive-margin effects on employment and finds that the privatization increased firms' total employment while it had little impact on employment per establishment. Appendix Section 10.5 shows that firms with better access to the Internet tended to locate new establishments in counties with higher household income and younger populations and with smaller distances to nodes.

4.3 Firms' Internal Communication and Geographic Expansion: An IV Approach

The reduced-form results show that the Internet privatization, which reduced the costs of accessing the Internet and ICT in general, increased firms' geographic span of control. Multiple channels could be at play in this effect. In this section, I use the LBD–CNUS matched sample and firms' intranet adoption as a proxy for internal communication costs to highlight the channel of firms' internal communication costs declining as a result of the privatization. Specifically, I take advantage of the previous reduced-form analysis and use an instrumental variable approach to identify the effect of intranet adoption on firms' geographic span of control.

Ideally, I would like to have a panel that records firms' intranet adoption status before and after the Internet privatization. Unfortunately, this type of panel data is not available. Nevertheless, as Internet-based intranets were first commercialized in 1996, after the Internet privatization, I create a time-varying indicator of a firm's intranet status by interacting the firm's intranet adoption in 1999 with a postprivatization indicator, i.e., $\text{Intranet}_{it} = \text{Intranet}_i \times \text{Post}_t$ for firm i in year t. The goal is to relate the firm's intranet adoption to its geographic expansion. The regression representing this relationship is as follows:

$$\text{Y}_{it} = \alpha_i + \gamma \text{Intranet}_{it} + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}, \tag{14}$$

where the dependent variable is the number of establishments of the firm and α_i is firm fixed effects. One concern is that a firm's ICT adoption might be correlated with its geographic expansion. For instance, a firm may expand and then decide to upgrade its internal management system, leading to reverse causality. To address this concern, I use the variation from Internet privatization (i.e., $\text{HQDistToNode}_i \times \text{Post}_t$) to instrument for firms' intranet adoption (i.e., Intranet_{it}). The IV regression takes the same form as Equation (14) but replaces the firm's intranet adoption status with its predicted likelihood of intranet adoption:

$$Y_{it} = \alpha_i + \gamma \widehat{\text{Intranet}}_{it} + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}, \tag{15}$$

where $\widehat{\text{Intranet}}_{it}$ is generated by the first-stage regression:

$$\text{Intranet}_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it}. \tag{16}$$

As the firms in the matched sample are, on average, larger and more likely to be multi-unit firms than firms in the baseline sample for the reduced-form analysis, I estimate the conditional probability of a firm belonging to the matched sample, i.e., the propensity score, and then apply the inverse propensity scores to reweight the matched subsample (see Chen et al., 2008). Finally, I use the matched sample up to 1999 to minimize the scope of measurement errors resulting from the construction of my time-varying intranet variable. Table 3 reports the results. Column (1) shows the first-stage estimate from Equation (16), showing that firms closer to NSFNET nodes were more likely to adopt an intranet after the Internet privatization. Column (2) shows the reduced-form estimate, which is consistent with the baseline estimates.[33] The IV estimate in column (3) shows that firms that adopted an intranet are associated with 1.235 more establishments, almost doubling the number relative to the average of 1.326.

The exclusion restriction requires that the instrument affect firms' geographic span of control only through their intranet adoption. I conduct two sets of analyses to test whether other online advanced applications affect the outcome. First, I follow the same procedure as that used to build the Intranet measure, construct indicators for adoption of other networks, and compare the first-stage estimates using these variables as outcomes. Appendix Table 17 shows that the estimated coefficients on other network adoptions are either smaller than that on Intranet or statistically insignificant. A longer distance to the node even predicts a higher likelihood of adopting the Internet, reflecting the fact that adoption of the basic Internet had reached saturation by the end of the 1990s. In the second analysis, I construct an indicator $\text{AdvancedOnlineNetwork}_{it}$, which represents firms' adoption of a broader set of advanced online networks (i.e., intranet, extranet, or EDI) and is set to one if a firm adopted any of these networks. Column (4) in Table 3 shows the corresponding estimate from the IV regression. While the first-stage F statistic is smaller than that from the Intranet regression, the point estimate is similar, which reassures us that the effect of intranet adoption is unlikely to be driven by adoption of other types of ICT.

Taken together, the difference-in-differences estimates based on the use of the Internet privatization as a natural experiment for firms' ICT adoption suggest that firms with better ICT access were able to expand geographically. The instrumental variable approach further underscores the role of intranet adoption—and the declines in firms' internal communication costs—in facilitating firms' geographic expansion.

In the following section, I incorporate key features of the reduced-form analysis into the struc-

[33]The reduced-form estimate is smaller than the baseline difference-in-differences estimates in the regressions weighted by firm employment shares but is almost the same as the unweighted estimate, suggesting that the inverse propensity score–adjusted regressions on the matched sample represent the full baseline sample well.

tural model and apply the instrument for ICT adoption that is developed here to the estimation. Moreover, I use the model to investigate the general equilibrium effects and efficiency gains from the Internet privatization.

5 Estimation of a Spatial Equilibrium Model

I estimate the spatial equilibrium model developed in Section 3. Key parameters concern the two communication costs and the extent to which they are affected by ICT adoption—one is the firm-wide communication cost, and the other cost depends on the pair of headquarters and establishment locations. These estimates are important for evaluating the efficiency gains from ICT improvements.

The estimation is performed in three steps. In the first step, I estimate the headquarters–establishment communication costs, which depend on firms' ICT adoption, by estimating a within-firm gravity equation derived in Section 3.3.1 using the establishment-level data. To account for the potential endogeneity of ICT adoption, I supplement the OLS analysis with an instrumental variable approach that uses the firm's proximity to the NSFNET nodes as an instrument. In the second step, I back out the state of technology, i.e., the scale parameters of the Fréchet distribution (T_s), for each location. In the last step, I jointly estimate the firm-wide communication costs and the fixed costs of setting up establishments and adopting ICT using the method of simulated moments. To overcome the computation difficulty arising from the firm's location choice problem, I apply the methodology developed in Arkolakis et al. (2021). Additionally, I define the location at the census division level. Nevertheless, this operationalization still captures meaningful firm expansion patterns. When multi-unit firms add establishments, a majority of the new establishments are located in census divisions different from those where the firms are headquartered.

Sections 5.1 describes the parameterization and externally calibrated parameters. Section 5.2–5.4 discuss the estimation in three steps.

5.1 Parameterization

Table 4 summarizes the model parameters. Panel A shows the assigned parameters, and Panel B shows the estimated parameters. I externally calibrate the elasticity of substitution across varieties (σ) to 4, the center value in the range of estimates used in the international trade literature (see Head and Mayer, 2014).[34]

The shape parameter of the Fréchet distributions of the establishment productivity draws is set to $\theta = 3.6$, the medium value used in Eaton and Kortum (2002).[35] This parameter governs

[34] $\sigma = 4$ implies a markup of approximately 33%.

[35] Fajgelbaum et al. (2019) estimate θ to be in the range of 2.43–2.84 at the state level. Tintelnot (2017) and

the dispersion of establishment locations' productivity draws and affects locations' substitutability, thus impacting firms' location choices. A larger value of θ implies a smaller dispersion of local productivity. Locations become closer substitutes, so the benefits of having larger sets of production locations decrease. The scale parameter of the Fréchet distribution, i.e., T_s, which summarizes the state of technology in each location, is estimated and discussed in the second step in Section 5.3.

I assume that firm productivity follows a log-normal distribution, where the mean and dispersion are set to -0.122 and 0.767, respectively, using the estimates from Guner et al. (2008), who use the 1997 US Census of Manufacturers to estimate the distribution of firm productivity.[36]

Trade costs are log-linear in the distance, measured in miles, between the production establishment (s) and the destination market (k): $\tau_{sk} = e^{\beta^\tau \log \text{Miles}_{sk}}$. I set the elasticity β^τ to 0.278, which implies a conventional trade elasticity of -1 (see Disdier and Head, 2008).

As one key set of parameters, I assume that headquarters–establishment communication costs ($d_{os\varphi}$) are log-linear in the distance, measured in miles, between the firm's headquarters and establishment. Importantly, I allow the elasticity of the communication costs with respect to distance to vary between firms with low and high ICT: $d_{os\varphi} = e^{\beta^d_\varphi \log \text{Miles}_{os}}$, for $s \neq o$. Communication costs within the headquarters are normalized to 1, i.e., $d_{oo} = 1$. Guided by the empirical result that having an intranet lowers a firm's internal communication costs, I use firms' intranet adoption as a proxy for ICT: Firms that adopted an intranet are associated with high ICT, and those without an intranet are associated with low ICT. I estimate the elasticities associated with low and high ICT, i.e., $\beta^d_{\text{Low ICT}}$ and $\beta^d_{\text{High ICT}}$, in the first-step estimation in Section 5.2.

Firm-wide communication costs take two values since ICT is discretized into two levels. Denote the one associated with low ICT by $\underline{h}$ and the one with high ICT by $\overline{h}$. Recall that the firm-wide communication cost acts as a shifter for firms' effective productivity; we can identify only the relative magnitude of the two values ($\underline{h}$ and $\overline{h}$). Therefore, I normalize the cost in the presence of higher ICT to 1, i.e., $\overline{h} = 1$, and estimate $\underline{h}$, which represents the productivity loss associated with low ICT in the third step in Section 5.4.

I parameterize the fixed costs of adopting ICT to be log-normally distributed. Furthermore, I add to the model the empirical finding that firms located closer to NSFNET nodes are more likely to adopt an intranet. Specifically, I assume that the mean of the log-normal distribution is linear in the log average distance to the nearest NSFNET node for firms headquartered in census division o: $\mu_o^{ICT} = \beta_1^{ICT} + \beta_2^{ICT} \log(\widetilde{\text{HQDistToNode}}_o)$.[37] The standard deviation of the

Hu and Shi (2019) assume $\theta = 7$ for EU countries. Antras et al. (2017) use the countries from which US firms import and estimate $\theta = 1.789$. Eaton and Kortum (2002) provide three measures of θ at 2.84, 3.60 and 8.28.

[36] Guner et al. (2008) estimate the distribution of firm productivity, defined as managerial ability, by matching the size distributions of US establishments. They assume that log-managerial ability is normally distributed. The estimated mean is -0.367, and the dispersion is 2.303. Since size is proportional to productivity in Guner et al. (2008) while it is proportional to productivity by a factor of $\sigma - 1$ in my setting, I apply a factor of $1/(\sigma - 1)$ to their estimated mean and dispersion to be consistent.

[37] To account for geographic area differences at the census division level, I normalize the average distance in

log-normal distribution is σ^{ICT}. Similarly, the fixed costs of setting up establishments are log-normally distributed, with mean μ^X_{os} and standard deviation σ^X, where the mean is log-linear in the distance between the headquarters and establishment location: $\mu^X_{os} = \beta^X_1 + \beta^X_2 \log(\text{Miles}_{os})$. I estimate these parameters regarding the fixed costs of ICT adoption and geographic expansion $(\beta^{ICT}_1, \beta^{ICT}_2, \sigma^{ICT}, \beta^X_1, \beta^X_2, \sigma^X)$, along with the firm-wide communication cost for low ICT ($\underline{h}$), in the third step in Section 5.4.

5.2 Estimating Headquarters–Establishment Communication Costs

I first identify the elasticity of location-pair communication costs with respect to distance and, importantly, how this elasticity varies by firms' ICT level.

Within-firm gravity equation. Section 3.3.1 derives a within-firm gravity equation that relates the within-firm establishment sales share to the costs of communication between the headquarters and establishment. Establishments that are far away from the headquarters face higher communication costs and thus a smaller sales share. Denote the firm's headquarters location by o, the set of locations by S, the ICT level by φ, and its sales share at establishment in s by $\zeta_{oS\varphi,s}$. By Equation (10), we can write the establishment's within-firm sales share, normalized by the sales share of the headquarters, as:

$$\log \tilde{\zeta}_{oS\varphi,s} = \underbrace{-\theta \log d_{os\varphi}}_{\text{Communication cost}} \underbrace{+\log\left(\sum_k \omega_{oS\varphi k}\, \tau_{sk}^{-\theta}\right)}_{\text{Weighted average market access}} + \xi_{oS\varphi} + \xi_s, \tag{17}$$

where $\omega_{oS\varphi k} = \frac{E_k P_k^{\sigma-1} \Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{oS\varphi k'}^{\frac{\sigma-\theta-1}{\theta}}}$. The terms on the right-hand side are the location-pair communication cost between headquarters o and establishment s for firms with ICT level φ; the average shipping costs from the establishment to all markets k, i.e., the establishment's market access, weighted by the corresponding market's demand share; a headquarters–set–ICT-specific component $\xi_{oS\varphi}$; and an establishment-specific component ξ_s.

There are a few details worth noting to take Equation (17) to the data. First, sales data were unavailable in the LBD until recently and are at the firm level. Fortunately, the LBD provides detailed employment data at the establishment level. Therefore, I instead use the within-firm *employment share* to conduct the estimation. Appendix 12.1 shows that the establishment employment share is of the same form as the sales share.

Second, to control for the establishment's market access, I approximate the weighted aver-

each census division by its land area; that is, $\widetilde{\text{HQDistToNode}}_o = \overline{\text{HQDistToNode}}_o / \text{LandArea}_o$. As the distance measure is a proxy of ICT accessibility, the scaled term measures the density of ICT accessibility per square mile. The normalization captures the fact that for larger areas, it is harder for an average firm to reach any node.

age market access by $(\phi + \phi_{oS\varphi}) \log \left(\sum_k \frac{N_k \bar{y}_k}{\sum_{k'} N_{k'} \bar{y}_{k'}} \tau_{sk'}^{-\theta} \right) \equiv (\phi + \phi_{oS\varphi}) \log \overline{MA}_s$, where N_k is the population of location k and $\bar{y}_k$ is the location's per capita income. That is, I approximate the establishment's market access by a linear function of the simple market access term ($\overline{MA}_s$) but allow the slope, i.e., $\phi_{oS\varphi}$, to vary across the headquarters location, other establishment locations, and firm ICT levels.[38]

Finally, I use the firm's intranet adoption as a proxy for ICT (φ). Denote the firm by i and its intranet adoption by Intranet_i. Then, the communication cost takes the form of $d_{ios\varphi} = e^{\beta_1^d \log \text{Miles}_{os} + \beta_2^d \log \text{Miles}_{os} \times \text{Intranet}_i}$. Combining Equation (17) with the parameterization of communication costs and trade costs, we can write the regression specification as:

$$\begin{aligned} \log \tilde{\zeta}_{ioS\varphi,s} = &-\theta\beta_1^d \log \text{Miles}_{os} - \theta\beta_2^d \log \text{Miles}_{os} \times \text{Intranet}_i \\ &+\phi_{oS1} \log(\overline{\text{MA}}_s) + \phi_{oS2} \log(\overline{\text{MA}}_s) \times \text{Intranet}_i \\ &+\xi_{oS1} + \xi_{oS2} \times \text{Intranet}_i + \xi_s + \varepsilon_{ioS\varphi,s}. \end{aligned} \tag{18}$$

All else constant, the employment share of an establishment decreases in the distance to the firm's headquarters, and this elasticity varies with the firm's intranet adoption. The error term $\varepsilon_{ioS\varphi,s}$ captures other factors affecting communication and trade costs that are orthogonal to the firm's location choice. It is worthwhile to note that the establishment location fixed effect ξ_s summarizes the establishment location's state of technology, wage costs, and average market access:

$$\xi_s = \theta \log(T_s) - (\theta + 1) \log(w_s) + \phi \log \overline{MA}_s. \tag{19}$$

Identification requires variation across nonheadquarters establishments, given a headquarters–set combination. Therefore, I further restrict the estimation sample to firms with establishments in at least three census divisions. Firms with an intranet versus those without help identify the coefficient on the interaction term between distance and intranet adoption. I include industry fixed effects to control for industry heterogeneity.

Given the estimates of the coefficients in Equation (18) and the value of θ, we can back out the elasticities of communication costs with respect to the headquarters–establishment distance. Denote the estimated coefficients on $\log \text{Miles}_{os}$ and $\log \text{Miles}_{os} \times \text{Intranet}_i$ by $\hat{b}_1^d$ and $\hat{b}_2^d$. Then, the estimates of elasticities for firms without and with an intranet are $\hat{\beta}^d_{\text{Low ICT}} = \hat{b}_1^d/\theta$ and $\hat{\beta}^d_{\text{High ICT}} = (\hat{b}_1 + \hat{b}_2)/\theta$, respectively. If an intranet indeed reduces communication costs between the establishment and headquarters, we should find a smaller elasticity (in magnitude) for firms that have adopted an intranet, i.e., $\mid \hat{\beta}^d_{\text{High ICT}} \mid < \mid \hat{\beta}^d_{\text{Low ICT}} \mid$.

[38] Given the firm's headquarters location, set of locations, and ICT level (i.e., intranet adoption status), the correlation between the model-derived market access and the linear approximation is 0.97, on average. The high correlation indicates that linear functions of market demand–weighted market access approximate the market access term reasonably well.

Instrumental variable. One concern is that firms selecting into ICT adoption might be systematically different. For instance, firms with large establishments in faraway locations may be more likely to adopt better ICT, leading to an upward bias of the impact of ICT. To address this concern, I supplement the OLS regression with an instrumental variable approach that exploits the Internet privatization and distance to Internet backbone nodes, as described in Section 4.3. In particular, I use the predicted probability of intranet adoption of a firm i, i.e., $\widehat{\text{Intranet}}_i$, as an instrument for Intranet_i and interactions between the predicted value and other variables, e.g., $\widehat{\log \text{Miles}_{os} \times \text{Intranet}_i} = \log \text{Miles}_{os} \times \widehat{\text{Intranet}}_i$, as instruments for the corresponding interaction terms.[39]

Estimation results. I use the LBD–CNUS matched sample to estimate Equation 18. Table (5) reports the estimation results. Columns (1)–(2) abstract away from ICT adoption, serving as a first pass for the relationship between establishment employment shares and their distances to the firm's headquarters. Column (1) includes observations throughout 1987–2007. The coefficient on Log(Miles) is estimated to be -0.172, indicating that a 10% reduction in the distance in miles between the headquarters and establishment census divisions leads to a 1.7% increase in the establishment's sales share. Columns (2)–(4) use observations for 1999, the year for which we have firms' ICT adoption information.

In the baseline regression in column (3), the coefficient on the distance between the headquarters and establishment census divisions is estimated at -0.652. As I calibrate θ to 3.6, the elasticity of communication costs with respect to the distance for firms without an intranet ($\beta^d_{\text{Low ICT}}$) is $0.181 = (0.652/3.6)$. The coefficient on the interaction of Log(Miles) and Intranet shows that the elasticity is *smaller* for firms with an intranet: $\beta^d_{\text{High ICT}}$ is $0.072 = ((0.652 - 0.394)/3.6)$, less than half that for firms without an intranet. These results suggest that technology reduces communication costs over long distances. Using the instrumental approach, column (4) shows that the difference in communication costs between firms with and without an intranet is even larger: $\beta^d_{\text{Low ICT}}$ and $\beta^d_{\text{High ICT}}$ are estimated at 0.334 and 0.057, respectively, reflecting an over 80% reduction in communication costs. One reason for the larger effect from the 2SLS estimates may be that given the same geographic footprints, firms initially subject to poor communication between the headquarters and establishments are more incentivized to adopt an intranet.

The elasticity of communication costs is smaller, especially for firms with an intranet, than that of trade costs with respect to distance. This implies that a local shock, e.g., a local productivity shock, diffuses to other locations at a faster rate through the multi-unit production channel within the firm than through the trade channel.[40]

Here, I interpret the coefficients on the distance between headquarters and establishments as

[39] Standard errors are calculated by 1,000 bootstrapped samples to take into account both the first- and second-stage regressions.

[40] Giroud and Mueller (2019) show that local housing price shocks spill over to other regions through firms' internal network, i.e., establishments with the same parent firm.

communication costs. One could also interpret them as physical shipping costs if the establishment needs to physically import production inputs such as intermediates from the headquarters. Nevertheless, Atalay et al. (2014) use the Commodity Flow Survey (CFS) and find little interplant shipping even within vertically integrated firms.

5.3 Estimating Local Productivity

The first-step regression in column (1) of Table 5 delivers a vector of estimates of fixed effect for each census division s and year t, i.e., ξ_{st}. In the second step, I decompose these fixed effect estimates to back out the scale parameters of the location-specific Fréchet distributions that represent the locations' state of technology T_s.

By appealing to the calibrated value of θ and Equation (19), which draws on the model structure, I construct "purified" location-specific fixed effects that are purged of the wage component as $\tilde{\xi}_{st} \equiv \hat{\xi}_{st} + (\theta+1)\log w_{st} = \theta \log(T_{st}) + \phi \log \overline{MA}_{st}$, where w_{st} is the education-adjusted average weekly wage of the manufacturing sector for census division s and year t.[41] Columns (1) and (2) in Table 18 report the raw and purified estimates, respectively, of the fixed effects for each census division in 1999 and normalize these estimates by the estimate for the New England census division. Take the Pacific census division (consisting of the states of Washington, Oregon and California) as an example. Once I take out the high wage there, the Pacific has the largest estimated purified fixed effect. On the other hand, the East South Central division (consisting of the states of Alabama, Kentucky, Mississippi and Tennessee) has the lowest value.[42]

To back out T_s, I need to estimate the coefficient on market access (ϕ). I follow the convention by approximating the location-specific state of technology (T_{st}) by the local R&D stock and then regress the purified location-specific fixed effects ($\tilde{\xi}_{st}$) on the logarithm of the local R&D stock ($\log \text{R\&D}_{st}$), the logarithm of local market access ($\log \overline{MA}_{st}$), a vector of year fixed effects (γ_t), and census division fixed effects (δ_s):[43]

$$\tilde{\xi}_{st} = b_0 + b_{RD} \log(\text{R\&D}_{st}) + \phi \log \overline{MA}_{st} + \gamma_t + \delta_s + u_{st}. \tag{20}$$

Table 6 shows the estimated coefficients. Columns (1) and (2) control for the location's R&D

[41] The education-adjusted wage is calculated by $w_{st}^{\text{adj}} = w_{st} \exp(\mu H_{st})$, where H_{st} is the average years of schooling in census division s and year t and μ is the return to schooling, which is set to 0.06 following Bils and Klenow (2000).

[42] The purified fixed effects depend on the value of θ, which is calibrated to 3.6 here, but the implied location's state of technology is highly correlated when I vary the value of θ.

[43] I construct the local R&D stock by the perpetual inventory method using industrial R&D expenditure. State-level R&D expenditure data are from the Survey of Industrial Research and Development, available from the NSF website. Before 1998, the R&D expenditure data were published only for odd years. Following Wilson (2009), I interpolate the data by averaging the values for the years before and after. For instance, $\text{R\&D}_{1990}^{\text{exp}} = (\text{R\&D}_{1989}^{\text{exp}} + \text{R\&D}_{1991}^{\text{exp}})/2$. Then, I calculate the R&D stock by $\text{R\&D}_t^{\text{stock}} = (1-\delta_{\text{R\&D}})\text{R\&D}_{t-1}^{\text{stock}} + \text{R\&D}_t^{\text{exp}}$, where I assume the depreciation rate to be 0.15.

stock and market access, respectively. As the baseline specification in column (3), I control for both terms. Consistent with the premise that the location's appeal increases in both the location's productivity (proxied by the local R&D stock) and market access, the coefficients on both terms are positive and statistically significant. In particular, the elasticity with respect to market access (i.e., $\hat{\phi}$) is estimated at 0.743. Then, I construct the state of technology for each census division by $\log(T_{st}) = (\tilde{\xi}_{st} - \hat{\phi} \log \overline{MA}_{st})/\theta$. Column (3) of Table 18 reports the state of technology for each census division, normalized by that of the New England census division. Although the state of technology is highly correlated with the purified fixed effect, the two terms differ due to market access. For instance, compared to the New England division, the Middle Atlantic has a higher local fixed effect but a lower state of technology, indicating that it is mostly better market access that drives up the Middle Atlantic's appeal.

5.4 Estimating Firm-Wide Communication Costs and Fixed Costs of ICT Adoption and Geographic Expansion

In the last step, I use the method of simulated moments to estimate the firm-specific communication cost associated with a low ICT level ($\underline{h}$), the mean and dispersion of the fixed costs of geographic expansion ($\beta_1^X, \beta_2^X, \sigma^X$) and those of the fixed costs of ICT adoption ($\beta_1^{ICT}, \beta_2^{ICT}, \sigma^{ICT}$).

Denote the vector of parameters to estimate as $\phi = \{\beta_1^X, \beta_2^X, \sigma^X, \underline{h}, \beta_1^{ICT}, \beta_2^{ICT}, \sigma^{ICT}\}$, the data moments as m, and the simulated moments as $\hat{m}(\phi)$. The estimate $\hat{\phi}$ minimizes the criterion function:

$$g(\phi) = [m - \hat{m}(\phi)]' W [m - \hat{m}(\phi)], \tag{21}$$

where W is the weighting matrix. I use the identity matrix as a weighting matrix ($W = I$).

Simulation. I simulate 10,000 firms for each location. Each firm is headquartered in its location of birth. Each firm draws a vector of 11 independent random variables. First, each firm independently draws a productivity z from log-normal distribution with mean μ^z and dispersion σ^z. Second, the firm draws a vector of 9 independent standard normal random variables. Given the firm's headquarters location o, I transform these random variables to the fixed costs of setting up establishments (f_{os}^X) in each location s. The fixed costs of the headquarters, i.e., f_{oo}^X, are set to zero. Finally, the firm draws a standard normal random variable that I transform to the fixed costs of ICT adoption (f_o^{ICT}), given the firm's headquarters location o.

Moments and identification. Table 7 summarizes the moments for estimation, where I use three sets of moments constructed from the matched LBD–CNUS sample. The first set of moments regards firms' expansion patterns across census divisions, including 1) the overall share of

multi-unit firms, 2) the share of multi-unit firms with employment below the median, and 3) the correlation of the share of firms that are headquartered in census division o and have establishments in another census division $s \neq o$ (i.e., $\%\text{Firms}_{os}$) and the logarithm of the miles between the two census divisions. These moments are informative of the fixed costs of setting up establishments. In particular, the overall share of multi-unit firms decreases in the average fixed costs and thus helps identify the mean of those fixed costs (β_1^X). The share of multi-unit firms with employment below the median is informative of the dispersion of fixed costs (σ^X). The idea is that only the most productive firms, which are also the largest firms, would become multi-unit if there were no dispersion in the fixed costs of setting up establishments. As these fixed costs become more dispersed, firms with low productivity may draw small fixed costs, allowing them to expand. The correlation moment helps identify the role of distance in the fixed costs (β_2^X).

The second set of moments regards firms' ICT adoption, including 1) the overall share of firms that adopt an intranet, 2) the share of adopting firms with employment below the median, and 3) the correlation between a firm's ICT adoption and the logarithm of the average distance to the nearest NSFNET node from the firm's headquarters location. Similarly, these moments help pin down the mean and dispersion of the fixed costs of ICT adoption and the role of distance to nodes in these fixed costs.

The third set of moments includes the correlation between a firm's expansion decision (i.e., whether the firm is multi-unit) and its ICT adoption. Along with the share of firms adopting ICT, the correlation helps identify the firm-specific communication cost associated with low ICT. The larger the difference in communication costs for low- and high-ICT firms, the higher is the correlation between firms' geographic expansion and ICT adoption.

Estimation results. Table 8 reports the estimates of the third-step estimation.[44] The firm-specific communication cost associated with having a low ICT level ($\underline{h}$) is estimated to be 1.335. As the cost associated with having a high ICT level is normalized to 1, this estimate translates to a $28.9\%(= \log 1.335 - \log 1)$ increase in firm-wide communication costs or, put differently, productivity disruption.

The fixed costs of setting up establishments (f_{os}^X) increase in the distance between the headquarters and the establishment, with an elasticity of 0.073. Column (1) of Table 19 reports the conditional average fixed costs in monetary value in each census division.[45] In terms of magnitude, the average fixed costs paid conditional on firms setting up additional establishments are \$2.37–\$4.57 million in 1999 US dollars. The South Atlantic census division is estimated to have the highest fixed costs, and the Pacific census division the second highest.[46] The estimated fixed

[44]Figure 16 plots the loss function against each parameter with the other parameters held at their estimated values, confirming that the estimates minimize the criterion function.

[45]I calculate the costs by assuming that the ratio of average sales to the fixed costs from the model is the same as that in the data.

[46]The South Atlantic census division consists of the states of Delaware, Maryland, Virginia, West Virginia,

costs are lowest in the West North Central division. Through the lens of the model, the fixed costs paid by multi-unit firms are approximately 17% of firms' total profits, on average. As the model does not distinguish between the sunk cost of setting up an establishment versus the flow cost paid to maintain remote establishments, the estimated fixed costs could include both types of costs.

The estimated fixed costs of ICT adoption are relatively smaller than those of setting up establishments. As reported in column (2) of Table 19, the average fixed costs paid by firms that adopt a high level of ICT are approximately \$1.16–\$1.45 million in 1999 US dollars. The fixed costs of ICT adoption may include not only the actual monetary costs paid for hardware and software to set up an intranet but also the value of the time required to upgrade the system, measured as forgone profits. These fixed costs increase in the location's ICT access, proxied by the location's average distance to the nearest NSFNET node, with an elasticity of 0.121. That is, a 10% reduction in the average distance is associated with a 1.2% decrease in the fixed costs of ICT adoption. As many small and single-unit firms also adopt an intranet in the data, there is large dispersion in the fixed costs of ICT adoption.

Model fit. The last column in Table 7 shows that the model is able to replicate the data moments well. To further validate the model, I compare the simulated bilateral expansion patterns, i.e., the share of firms that are headquartered in census division o and have establishments in census division s, to those shares from the data. Ideally, I would use the bilateral expansion shares from the LBD. Unfortunately, these bilateral expansions often have small sample sizes. Data privacy policies from the Census Bureau thus prevent me from disclosing these data. Therefore, I turn to an alternative dataset—the manufacturing package from the National Establishment Time Series (NETS) database—to calculate the bilateral expansion patterns. NETS is a comprehensive dataset that covers the universe of US establishments in the manufacturing and related sectors.[47] The database is comparable to the LBD in terms of its geographic coverage and firm ownership linkages. Figure 17 plots the model-simulated bilateral expansion patterns against data patterns from NETS, adjusted by a constant share difference. The correlation between the model-simulated moments and the data moments is high, at approximately 0.76. These shares are affected not only by the fixed costs of setting up establishments but also by the state of technology for each location that is estimated in the second step. Overall, the model does a good job in matching the targeted and untargeted moments.

North Carolina, South Carolina, Georgia and Florida, as well as the District of Columbia. The Pacific census division consists of the states of California, Oregon, Washington. I excluded noncontiguous states including Alaska and Hawaii.

[47] Barnatchez et al. (2017) provide detailed assessments of the NETS database and compare it to confidential US Census data. Rossi-Hansberg et al. (2021) use the NETS database and document a diverging concentration at the local and national levels.

6 Efficiency Gains from Internet Privatization

I use the estimated model to study the efficiency gains from the Internet privatization in equilibrium. Section 4 finds that the Internet privatization increased firms' geographic span of control using a difference-in-differences approach. What are the general equilibrium effects, in which the prices of manufacturing goods adjust endogenously? What are the efficiency gains, and how are they distributed across locations?

Through the lens of the model, I find that the Internet privatization increased efficiency by approximately 1.3% at the national level. Furthermore, multi-unit production plays a significant role in shaping the geographic distribution of these efficiency gains.

Simulation of Internet privatization. The reduced-form estimate shows that the privatization increased the average number of census divisions in which a firm had establishments by 2.56%.[48] I mimic the Internet privatization by reducing the fixed costs of ICT adoption to match this reduced-form estimate.

As the model is estimated to match moments in the postprivatization economy in 1999, I first back out the prereform average fixed cost of ICT in the partial equilibrium model, fixing the equilibrium prices to those in the postprivatization equilibrium. I do so by raising the average distance to nodes proportionally to the level such that the simulated changes in the average number of census divisions per firm match the reduced-form estimate. Denote the larger prereform distance by $\log(\widetilde{\text{HQDistToNode}}_{o,\text{pre}})$ and the associated average fixed costs of ICT by $\mu^{ICT}_{\text{pre}} = \beta^{ICT}_1 + \beta^{ICT}_2 \log(\widetilde{\text{HQDistToNode}}_{o,\text{pre}})$. To match a 2.56% increase in the number of operating locations per firm, the prereform costs μ^{ICT}_{pre} are 80% higher than the postreform costs. Then, I use these prereform costs to simulate the full model that allows equilibrium prices to adjust accordingly.

Efficiency gains. Columns (1)–(3) in Table 9 compare the change in average number of locations (i.e., census divisions) per firm from the reduced-form estimate, model-simulated partial equilibrium effect, and general equilibrium effect, respectively. By design, the change in column (2) exactly matches the reduced-form estimate in column (1). Allowing prices to adjust endogenously, the last column shows that due to tougher market competition, the general equilibrium effect on firms' geographic expansion is smaller than that in the partial equilibrium: the average number of census divisions per firm increases by 1.71, two-thirds of the magnitude when aggregate prices are fixed.

The second row shows that through the lens of the model, the Internet privatization increases

[48] Column (3) in Table 2 Panel B shows that the estimated coefficient on the interaction term HQDistToNode × Post is −0.048. Taking into account that the average distance to node is 130 miles and that the average dependent variable is 2.439, we can translate the estimate into a 2.56% increase in the average census division per firm ($= 0.048 \times 130/100/2.439 \times 100\%$).

efficiency by 1.3% at the national level.[49] This is a nontrivial increase if we consider it a permanent efficiency gain. To highlight the role of firms' geographic expansion in improving efficiency, I calculate the efficiency changes when firms' locations are fixed. The last row suggests that approximately 40% ($= 1 - 0.80/1.29$) of the efficiency gains are accounted for by firms' reoptimization of their geographic coverage. Improvements to the productivity of firms' existing establishments—including their headquarters and nonheadquarters establishments in other locations—account for the remaining 60% of the efficiency gains.

Last, to shed light on the various channels of the efficiency gains, I decompose the local efficiency gains in each location to the contributions from different types of firms, in particular local firms (i.e., firms headquartered in that location) and outside firms (i.e., firms headquartered in another location). For outside firms, I further divide them into four groups depending on whether they set up establishments in the location before and after the Internet privatization: "stayers" denote outside firms that have establishments in the location both before and after Internet privatization; "entrants" and "exiters" denote outside firms that entered or exited the location afterward, respectively; and "never-comers" denote outside firms that do not have establishments in the location either before or after the Internet privatization in the location.[50]

Table 10 shows that multi-unit production plays a significant role in shaping local efficiency. Take the New England census division, for example. Outside firms account for more than four-fifths of the local efficiency gains: stayers and entrants contribute 17% and 53%, respectively, while exiters reduce local efficiency by 7% due to higher shipping costs. Those outside firms that have never set up local establishments account for approximately 20% of the changes through trade—both the traditional trade channel from their headquarters and the third-location trade channel from their nonheadquarters establishments. Local firms, in contrast, account for less than one-fifth of the local efficiency gains. The last row shows the average contribution from each type of firm. In total, stayers, entrants, and exiters account for over 60% of the local efficiency gains, underscoring the importance of multi-unit production across locations in determining local efficiency gains.

7 Policy Simulations

As it did through the investment in NSFNET, the government continues to make significant investments in ICT. The research on the benefits from these investments, however, is inconclusive. The recent infrastructure bill in the US, which devoted $65 billion to ensuring access to high-speed Internet, has renewed the discussion. In this section, I simulate two policies that reduce the costs of ICT adoption—one at the local level and the other at the national level—to shed light

[49] Changes in local efficiency are captured by changes in the inverse of the local price index. I aggregate to the national level by taking the average changes, weighted by local consumption.

[50] Appendix 13.1 provides details on the decomposition of the efficiency gains.

on a new perspective of evaluating policies aimed at improving ICT access. I find it crucial to take multi-unit production into account when we evaluate the efficiency gains from these policies, as firms' multi-unit production and geographic expansion are important channels through which the benefits from technology improvement can spread across locations. Therefore, a coordinated national policy is preferable to uncoordinated local policies, as the latter do not internalize the positive geographic spillover.

7.1 Unilateral ICT Cost Reduction

Panel A of Figure 8 shows the averages of the estimated fixed costs of ICT adoption for each census division. The differences in ICT costs are driven by the location's average distance to NSFNET nodes. Consistent with the premise that the West Coast had better ICT infrastructure and talent pools, firms in the Pacific census division had the lowest ICT adoption costs. In contrast, firms in the New England, Middle Atlantic, East South Central and West South Central census divisions faced higher ICT costs.

In the first counterfactual exercise, I simulate a policy that helps local firms in the West South Central states, including Arkansas, Louisiana, Oklahoma and Texas, to reduce their ICT costs and catch up with Pacific firms. For instance, local governments might expand and upgrade broadband infrastructure so that firms have better access to high-speed Internet and advanced business applications such as intranets. I simulate such a policy by reducing West South Central's average fixed costs of ICT adoption to the same level as those in the Pacific, a cost reduction of approximately 25%. This cost reduction in the West South Central census division increases the local ICT adoption rate by 4.7%. Because of the complementarity between ICT adoption and geographic expansion, the local share of multi-unit firms increases by 1.4%. Panel B of Figure 8 shows where those West South Central firms expand their production. The Middle Atlantic, New England, and Pacific census divisions are among the favorite destinations. Consistent with the model prediction, these locations are relatively far away but have high productivity. The expansion patterns suggest that ICT infrastructure improvements in the South can affect other regions, particularly those in the North, through firms' expansion.

Panel C of Figure 8 shows the geographic distribution of efficiency gains from this local ICT cost reduction. As a direct effect, local efficiency in the West South Central census division increases by 0.05%.[51] Moreover, other locations benefit substantially from this local ICT cost reduction. For instance, efficiency in the New England census division, the furthest location, increases by 0.02%, which is two-fifths of the direct impact in the West South Central census division. The far-reaching effects could be attributed to two channels—trade and multi-unit production. To disentangle the operation of these two channels, I compare the benchmark model with an alternative

[51] Together with the 25% drop in the cost of ICT, we can translate these changes into an elasticity of efficiency with respect to the ICT cost of approximately -0.002.

model that shuts down the multi-unit production channel.[52] Panel D shows that a trade-only model would underestimate the geographic scope of the effects of a local cost reduction. The gains are geographically confined to the West South Central census division and decay rapidly in the distance. One key driver of the differences between the two models is the elasticity of communication costs and trade costs with respect to the distance. The estimated elasticity of communication costs is 0.072 and 0.181, respectively, for intranet adopters and nonadopters. Even for intranet nonadopters, which bear high costs of communication between establishments and headquarters, the elasticity is smaller than that of trade costs with respect to the distance. Therefore, firms' multi-unit production is an important channel through which a local shock can spill over across locations.

Decomposition of efficiency gains. I break down the role of multi-unit production in transmitting local ICT improvements to the rest of the economy. I do so by decomposing the efficiency gains in each location into the contributions from different types of firms, as described in Section 6, i.e., local firms and outside firms including stayers, entrants, exiters, and never-comers.

Appendix Table 20 reports the results. The efficiency gains in the West South Central census division, where ICT improvements occur, are primarily driven by the productivity increases of local firms headquartered in the location, as the fixed costs of ICT adoption decrease. In other locations, however, outside firms account for the majority of the efficiency changes. On average, stayers contribute approximately half of the efficiency increase in the other locations, driven by the productivity increase of the incumbent establishments set up by multi-unit firms headquartered in the West South Central census division. The geographic expansion of the West South Central census division further enhances the positive spillover to other locations. This effect is reflected by the contribution from entrants, i.e., those West South Central firms that expand to other locations after ICT improvements, which accounts for 32% of the efficiency change in the other census divisions, on average. Meanwhile, as markets become more competitive, firms from other locations contract, leading to a decline in efficiency. Exiters, i.e., those firms that exit the location as a result of the entry of more productive West South Central firms, have a negative impact, of approximately -2% on average, on other locations' efficiency. Never-comers contribute 25% of the efficiency changes, driven by spillover through trade. Finally, local firms, which are headquartered in the location, play a minimal role in local efficiency gains. If anything, they are less likely to adopt ICT and downsize their production, leading to an efficiency loss.

The lower panel of Table 20 reports the efficiency gains and the corresponding decomposition for each census division. Due to the heterogeneity in locations' initial shares of multi-unit firms and the expansion of West South Central firms, the contribution from each type of firm varies across locations. Nonetheless, multi-unit production, which includes stayers, entrants and exiters,

[52] In a trade-only model, the ICT cost reduction in the West South Central census division is designed to generate the same direct local efficiency gains in the West South Central division as in the benchmark model. The goal is to compare the distributional effects between the benchmark and trade-only models.

is the most important determinant of the geographic distribution of efficiency gains.

7.2 Universal ICT Cost Reduction and Equalization

Now consider an alternative policy issued by the federal government to lower the costs of ICT for all locations. Specifically, I lower the ICT costs in every location to the same level as those in the Pacific census division, as shown in Panel A of Figure 9. The cost reduction ranges from 39% in the New England census division to 10% in the Mountain census division, leading to a 4.5% increase in the nationwide ICT adoption rate. Panel B of Figure 9 shows the corresponding changes in the share of multi-unit firms in each census division. Closely following the changes in ICT costs, locations that experience the largest cost reductions see the greatest increases in the share of multi-unit firms. It is worthwhile to note that driven by the equilibrium force, the Pacific census division, which does not experience changes in ICT costs, shows a decrease in multi-unit firms due to market competition.

The bars on the left in Panel C of Figure 9 show the efficiency gains across locations. Despite the differential changes in ICT costs across locations, the differences in efficiency gains are smaller as a result of the geographic spillover through trade and multi-unit production. On average, local efficiency increases by 0.23%.[53] I compare these efficiency gains to those from another set of policies that take place at the local level and that reduce ICT costs individually for each location. Each bar on the right for each census division corresponds to a local policy that reduces the fixed costs of ICT adoption only in that census division, keeping the costs constant for the other census divisions. In each location, the magnitude of cost reduction in the local policy is the same as that in the federal policy. However, these local policies lead to smaller local gains. On average, the federal policy yields an elasticity of efficiency with respect to the ICT cost that is more than 4 times larger than that from local policies, indicating that a coordinated policy across locations is preferable to uncoordinated local policies.

I further compare these two policies in a trade-only model. As shown in Panel D of Figure 9, absent the spillover across locations through multi-unit production, the additional benefits from a universal rather than local cost reduction are smaller.

Taken together, these results underscore the importance of taking multi-unit production into account when we evaluate the gains from ICT and policy proposals that lower ICT costs. multi-unit production and firms' geographic expansion reinforce the overall gains from ICT when locations lower their ICT costs in a coordinated manner.

[53] An increase of 0.25% of consumption on goods is approximately 11–12 billion US dollars. An equivalent policy of subsidizing firm ICT adoption would cost approximately 9 billion US dollars to achieve the same increase in ICT adoption.

8 Conclusion

Recent developments in ICT have widened firms' geographic span of control, allowing them to expand production across locations. This paper provides empirical evidence relating firms' ICT adoption and their geographic expansion. More importantly, the paper provides a quantitative framework to study this novel source of efficiency gains from technology improvement through firm geographic expansion.

The empirical analysis leverages US Census microdata with establishment-level ownership linkages, geographic locations and ICT adoption. Firm-level evidence shows that firms that have adopted an intranet, which reduces firms' internal communication costs, are more likely to expand geographically; meanwhile, they are more likely to communicate within the firm.

Guided by these empirical findings, the paper proposes and estimates a model of firm ICT adoption and geographic expansion. The model generates economies of scale by allowing firms to pay a fixed cost of adopting advanced ICT to reduce the communication costs from the headquarters to all establishments. Here, ICT adoption and geographic expansion are complements to each other.

I estimate the model by matching firms' geographic expansion patterns and ICT adoption observed in the data. In particular, I use a model-derived within-firm gravity equation to estimate the elasticities of headquarters–establishment communication costs with respect to distance for firms with and without intranets. The estimates show that adopting an intranet can reduce the elasticity by over 50%. To account for endogeneity of firms' ICT adoption, I develop an instrumental variable that exploits quasi-experimental variation from a milestone in the history of US Internet development: the Internet privatization of 1995, which greatly reduced ICT costs. Moreover, the estimated model suggests that the Internet privatization increased aggregate efficiency by approximately 1.3%—where over 60% of this increase is accounted for by multi-unit firms.

Finally, the policy counterfactuals suggest that to improve local ICT access and local efficiency, a policy coordinated across locations can be more effective than uncoordinated local policies. Efficiency gains from local improvements in ICT might spill over to other locations through multi-unit firms. Compared to those in an alternative trade-only model, the efficiency gains from ICT improvements are more geographically dispersed when we take into account firms' multi-unit production and geographic expansion.

References

Aarland, K., J. C. Davis, J. V. Henderson, and Y. Ono (2007). Spatial organization of firms: The decision to split production and administration. *The RAND Journal of Economics 38*(2), 480–494.

Abadie, A. (2005). Semiparametric difference-in-differences estimators. *The Review of Economic Studies 72*(1), 1–19.

Aghion, P., A. Bergeaud, T. Boppart, P. J. Klenow, and H. Li (2019). A theory of falling growth and rising rents. Technical report, National Bureau of Economic Research.

Akerman, A., I. Gaarder, and M. Mogstad (2015). The skill complementarity of broadband internet. *The Quarterly Journal of Economics 130*(4), 1781–1824.

Akerman, A., E. Leuven, and M. Mogstad (2022). Information frictions, internet, and the relationship between distance and trade. *American Economic Journal: Applied Economics 14*(1), 133–63.

Antràs, P., E. Fadeev, T. C. Fort, and F. Tintelnot (2022). Global sourcing and multinational activity: A unified approach. Technical report, National Bureau of Economic Research.

Antras, P., T. C. Fort, and F. Tintelnot (2017). The margins of global sourcing: Theory and evidence from us firms. *American Economic Review 107*(9), 2514–64.

Aral, S., E. Brynjolfsson, and D. Wu (2006). Which came first, it or productivity? virtuous cycle of investment and use in enterprise systems. *Virtuous cycle of investment and use in enterprise systems*.

Arkolakis, C., F. Eckert, and R. Shi (2021). Combinatorial discrete choice.

Atalay, E., A. Hortaçsu, and C. Syverson (2014). Vertical integration and input flows. *American Economic Review 104*(4), 1120–48.

Barnatchez, K., L. D. Crane, and R. Decker (2017). An assessment of the national establishment time series (nets) database.

Baslandze, S. (2016). The role of the it revolution in knowledge diffusion, innovation and reallocation.

Bernard, A. B. and J. B. Jensen (2007). Firm structure, multinationals, and manufacturing plant deaths. *The Review of Economics and Statistics 89*(2), 193–204.

Bils, M. and P. J. Klenow (2000). Does schooling cause growth? *American economic review 90*(5), 1160–1183.

Bloom, N., L. Garicano, R. Sadun, and J. Van Reenen (2014). The distinct effects of information technology and communication technology on firm organization. *Management Science 60*(12), 2859–2885.

Bloom, N., R. Sadun, and J. Van Reenen (2012). Americans do it better: Us multinationals and the productivity miracle. *American Economic Review 102*(1), 167–201.

Bresnahan, T. (2010). General purpose technologies. In *Handbook of the Economics of Innovation*, Volume 2, pp. 761–791. Elsevier.

Brynjolfsson, E. and L. Hitt (1996). Paradox lost? firm-level evidence on the returns to information systems spending. *Management science 42*(4), 541–558.

Brynjolfsson, E. and L. M. Hitt (2003). Computing productivity: Firm-level evidence. *Review of economics and statistics 85*(4), 793–808.

Brynjolfsson, E. and S. Yang (1996). Information technology and productivity: a review of the literature. *Advances in computers 43*, 179–214.

Cao, D., H. R. Hyatt, T. Mukoyama, and E. Sager (2019). Firm growth through new establishments. *Available at SSRN*.

Chen, X., H. Hong, and A. Tarozzi (2008). Semiparametric efficiency in gmm models with auxiliary data. *The Annals of Statistics 36*(2), 808–843.

Dedrick, J., V. Gurbaxani, and K. L. Kraemer (2003). Information technology and economic performance: A critical review of the empirical evidence. *ACM Computing Surveys (CSUR) 35*(1), 1–28.

Disdier, A.-C. and K. Head (2008). The puzzling persistence of the distance effect on bilateral trade. *The Review of Economics and statistics 90*(1), 37–48.

Eaton, J. and S. Kortum (2002). Technology, geography, and trade. *Econometrica 70*(5), 1741–1779.

Eckert, F., S. Ganapati, and C. Walsh (2020). Skilled scalable services: The new urban bias in economic growth. *Available at SSRN 3736487*.

Fajgelbaum, P. D., E. Morales, J. C. Suárez Serrato, and O. Zidar (2019). State taxes and spatial misallocation. *The Review of Economic Studies 86*(1), 333–376.

Falck, O., R. Gold, and S. Heblich (2014). E-lections: Voting behavior and the internet. *American Economic Review 104*(7), 2238–65.

Forman, C., A. Goldfarb, and S. Greenstein (2003). The geographic dispersion of commercial internet use. *Rethinking rights and regulations: Institutional responses to new communication technologies*, 113–45.

Forman, C., A. Goldfarb, and S. Greenstein (2012). The internet and local wages: A puzzle. *American Economic Review 102*(1), 556–75.

Fort, T. C. (2017). Technology and production fragmentation: Domestic versus foreign sourcing. *The Review of Economic Studies 84*(2), 650–687.

Fort, T. C. and S. D. Klimek (2018, June). The Effects of Industry Classification Changes on US Employment Composition. Working Papers 18-28, Center for Economic Studies, U.S. Census Bureau.

Fort, T. C., J. R. Pierce, and P. K. Schott (2018). New perspectives on the decline of us manufacturing employment. *Journal of Economic Perspectives 32*(2), 47–72.

Frazer, K. D. (1996). *NSFNET: A partnership for high-speed networking: Final report, 1987-1995*. Merit Network.

Giroud, X. (2013). Proximity and investment: Evidence from plant-level data. *The Quarterly Journal of Economics 128*(2), 861–915.

Giroud, X., S. Lenzu, Q. Maingi, and H. Mueller (2021). Propagation and amplification of local productivity spillovers. Technical report, National Bureau of Economic Research.

Giroud, X. and H. M. Mueller (2019). Firms' internal networks and local economic shocks. *American Economic Review 109*(10), 3617–49.

Goldfarb, A. (2006). The (teaching) role of universities in the diffusion of the internet. *International Journal of Industrial Organization 24*(2), 203–225.

Goldfarb, A. and C. Tucker (2019). Digital economics. *Journal of Economic Literature 57*(1), 3–43.

Greenstein, S. (2015). *How the internet became commercial: Innovation, privatization, and the birth of a new network*. Princeton University Press.

Greenstein, S. (2020). The basic economics of internet infrastructure. *Journal of Economic Perspectives 34*(2), 192–214.

Gumpert, A., H. Steimer, and M. Antoni (2022). Firm organization with multiple establishments. *The Quarterly Journal of Economics 137*(2), 1091–1138.

Guner, N., G. Ventura, and Y. Xu (2008). Macroeconomic implications of size-dependent policies. *Review of Economic Dynamics 11*(4), 721–744.

Hanlon, W. W., S. Heblich, F. Monte, and M. B. Schmitz (2022). A penny for your thoughts. Technical report, National Bureau of Economic Research.

Head, K. and T. Mayer (2014). Gravity equations: Workhorse, toolkit, and cookbook. In *Handbook of international economics*, Volume 4, pp. 131–195. Elsevier.

Hirano, K. and G. W. Imbens (2004). The propensity score with continuous treatments. *Applied Bayesian modeling and causal inference from incomplete-data perspectives 226164*, 73–84.

Hjort, J. and J. Poulsen (2019). The arrival of fast internet and employment in africa. *American Economic Review 109*(3), 1032–79.

Hsieh, C.-T. and E. Rossi-Hansberg (2019, June). The industrial revolution in services. Working Paper 25968, National Bureau of Economic Research.

Hu, K. and R. Shi (2019). Solving combinatorial discrete choice problems in heterogeneous agent models.

Jia, P. (2008). What happens when wal-mart comes to town: An empirical analysis of the discount retailing industry. *Econometrica 76*(6), 1263–1316.

Jiao, Y. and L. Tian (2019). Geographic fragmentation in a knowledge economy. Technical report, Working Paper.

Jorgenson, D. W. (2001). Information technology and the us economy. *American Economic Review 91*(1), 1–32.

Jorgenson, D. W., M. S. Ho, and K. J. Stiroh (2003). Growth of us industries and investments in information technology and higher education. *Economic Systems Research 15*(3), 279–325.

Juhász, R. and C. Steinwender (2018). Spinning the web: Codifiability, information frictions and trade. *NBER working paper*.

Lashkari, D., A. Bauer, and J. Boussard (2018). Information technology and returns to scale. *Available at SSRN 3458604*.

Ma, Y. (2022). Specialization in a knowledge economy. *Available at SSRN 4052990*.

McKnight, L. W. and J. P. Bailey (1998). *Internet economics*. Mit Press.

Oberfield, E., E. Rossi-Hansberg, P.-D. Sarte, and N. Trachter (2020). Plants in space. Technical report, National Bureau of Economic Research.

Oliner, S. D. and D. E. Sichel (2000). The resurgence of growth in the late 1990s: is information technology the story? *Journal of economic perspectives 14*(4), 3–22.

Ramondo, N. and A. Rodríguez-Clare (2013). Trade, multinational production, and the gains from openness. *Journal of Political Economy 121*(2), 273–322.

Robins, J. M., M. A. Hernan, and B. Brumback (2000). Marginal structural models and causal inference in epidemiology. *Epidemiology 11*(5), 550–560.

Rossi-Hansberg, E., P.-D. Sarte, and N. Trachter (2021). Diverging trends in national and local concentration. *NBER Macroeconomics Annual 35*, 115–150.

Rubinton, H. (2020). The geography of business dynamism and skill biased technical change. *FRB St. Louis Working Paper* (2020-020).

Steinwender, C. (2018). Real effects of information frictions: When the states and the kingdom became united. *American Economic Review 108*(3), 657–96.

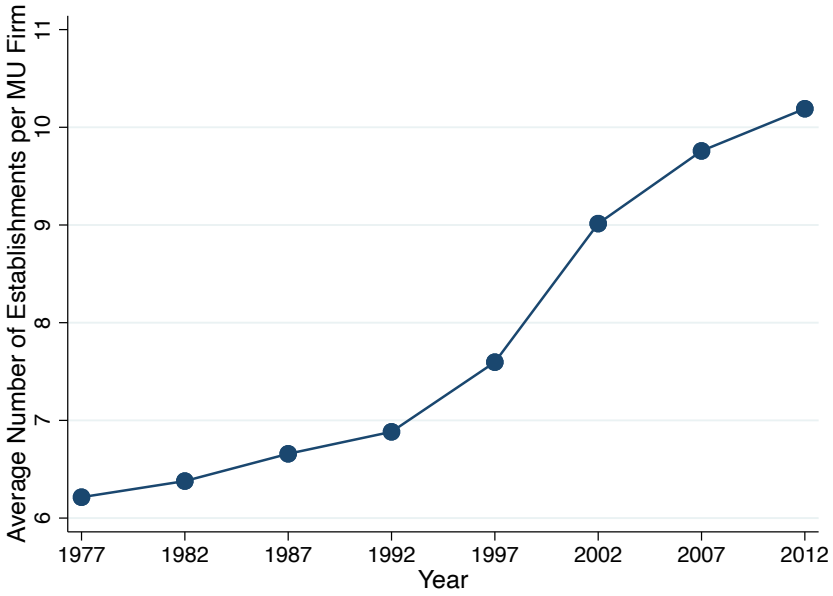
Stiroh, K. J. (2002). Information technology and the us productivity revival: what do the industry data say? *American Economic Review 92*(5), 1559–1576.

Tintelnot, F. (2017). Global production with export platforms. *The Quarterly Journal of Economics 132*(1), 157–209.

Van Reenen, J., M. Draca, and R. Sadun (2007). Productivity and icts: a review of the evidence.

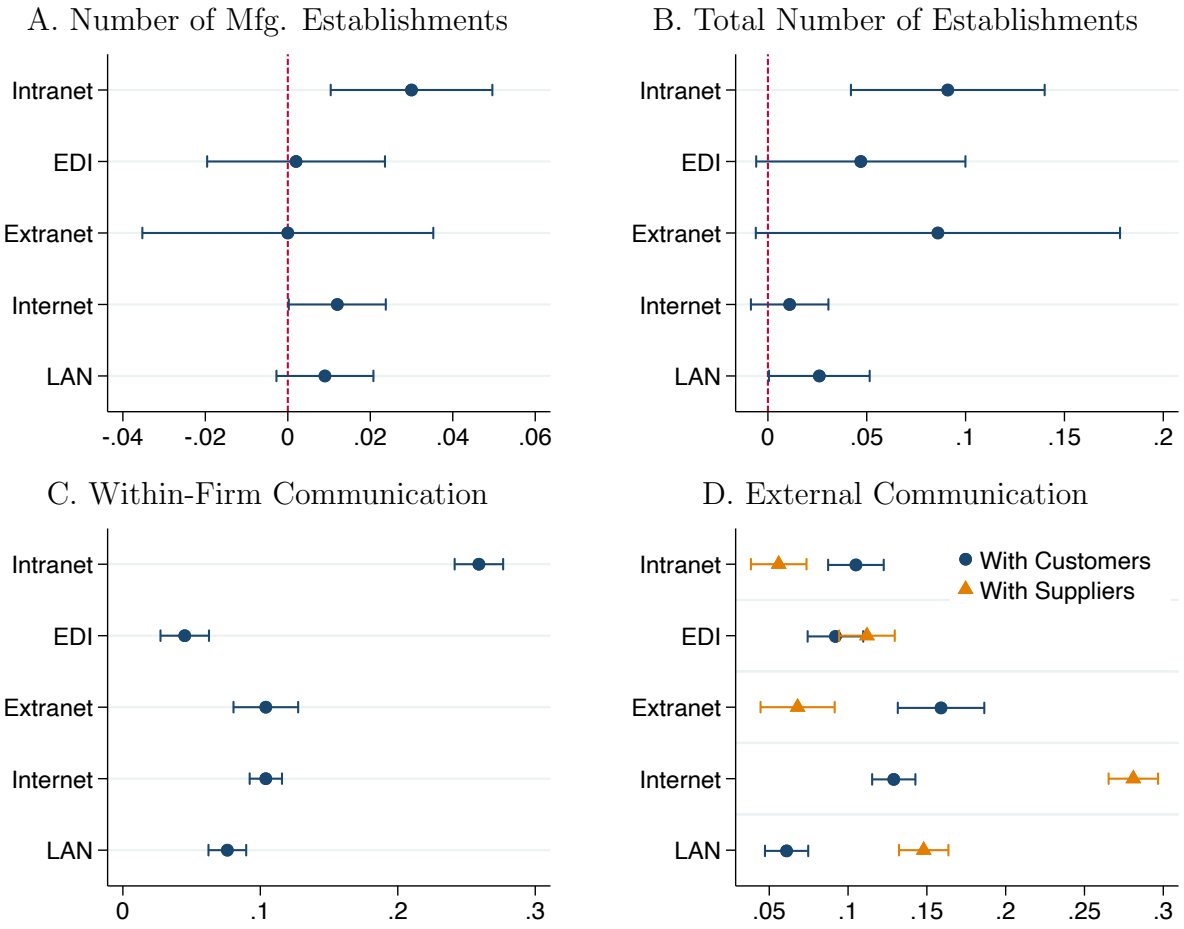
Wilson, D. J. (2009). Beggar thy neighbor? the in-state, out-of-state, and aggregate effects of r&d tax credits. *The Review of Economics and Statistics 91*(2), 431–436.

Figure 1: **Number of Establishments per Firm for Multi-Unit Firms from 1977 to 2012**



Notes: This figure plots the average number of establishments per firm for multi-unit firms during 1977 and 2012, using the Longitudinal Business Database (LBD). Multi-unit firms are firms that operate more than one establishment. See Section 2 for details on data sources and construction of variables.

Figure 2: **ICT Adoption, Expansion, and Communication**



Notes: Panels A and B use the matched sample of the Longitudinal Business Database (LBD) and the Computer Network Use Supplement (CNUS) and plot the coefficients of a regression of the form:

$$\Delta Y_{i,97-02} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,97}\gamma + \varepsilon_{i,97-02},$$

where the dependent variables $\Delta Y_{i,97-02}$ $(= \log Y_{i,02} - \log Y_{i,97})$ are the growth rate from 1997 to 2002 of firm i in the number of establishments per firm in the manufacturing sector (Panel A) and the total number of establishments per firm in all sectors (Panel B), respectively. Independent variables include indicators set to one if firm i adopted Intranet, Electronic data interchange (EDI), Extranet, Internet, and Local area network (LAN) by 1999. $X_{i,97}$ is a vector of firm's initial characteristics in 1997, including the logarithm of employment, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS Level. Confidence intervals are at the 95% level.

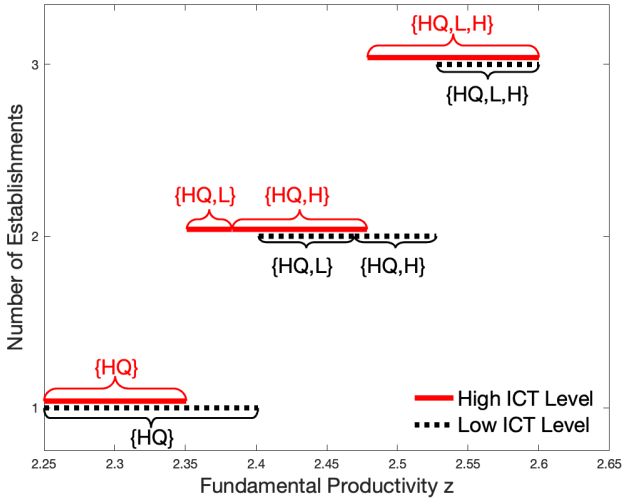
Panels C and D use the 1999 Computer Network Use Supplement (CNUS) sample and plot the coefficients of a regression of the form:

$$Y_{i,99} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,99}\gamma + \varepsilon_{i,99},$$

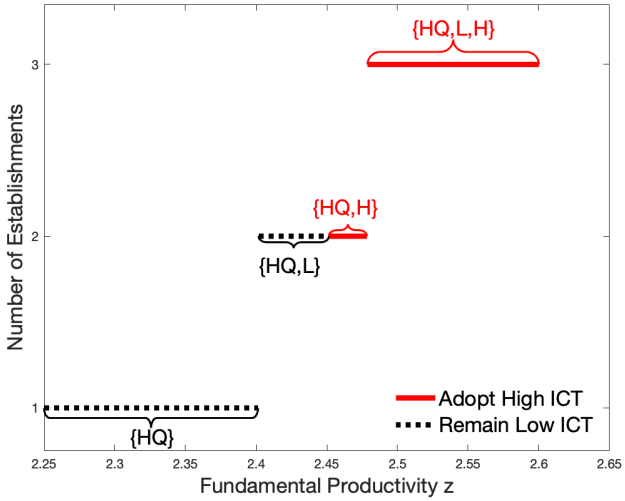
where the dependent variables are indicators set to one if any establishment of the firm provides information to other company units (in Panel A), external customers (triangle markers in Panel B), and external suppliers (circle markers in Panel B), respectively. $X_{i,99}$ is a vector of firm characteristics in 1999, including the logarithm of capital to labor ratio, the logarithm of employment, the skill mix measured by the ratio of nonproduction workers to production workers, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS Level. Confidence intervals are at the 95% level.

Figure 3: **Firm Location Choice and ICT Adoption: An Illustration with Three Locations**

A. Location Choice



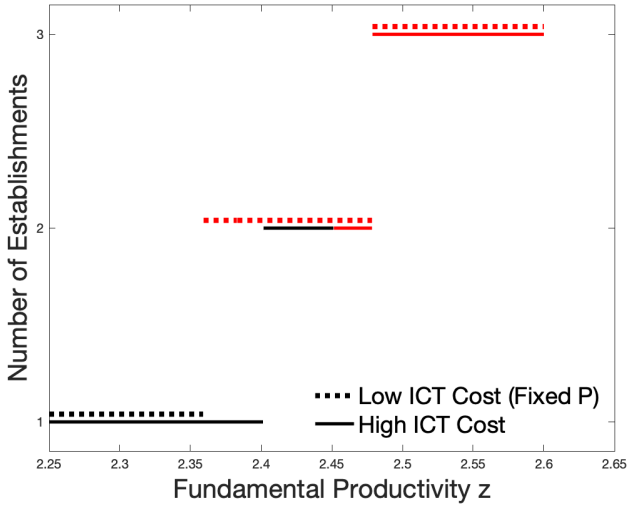
B. Location Choice and ICT Adoption



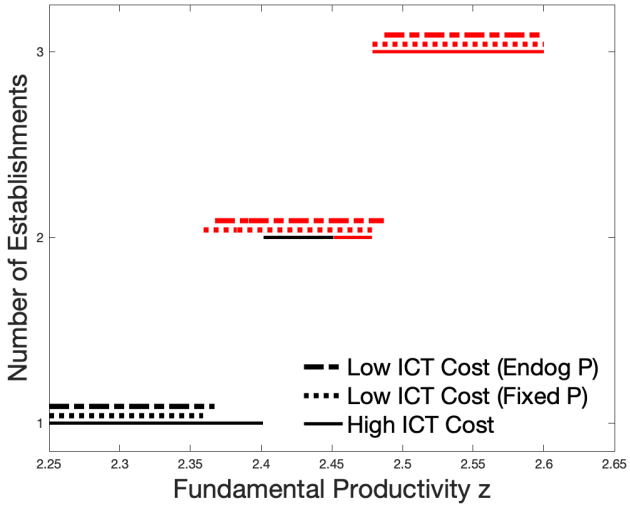
Notes: These figures plot the policy functions of location choices and ICT adoption against productivity in a simple example with three locations $\{HQ, L, H\}$ and for firms headquartered in HQ. Panel A plots the number of establishments and the set of locations against productivity for a low ICT level (the black dotted line) and a high ICT level (the red solid line), respectively. Panel B plots the joint decision of location choice and ICT adoption against productivity. The dashed black line corresponds to low ICT, and the red solid line corresponds to high ICT.

Figure 4: **Equilibrium Effects of an ICT Cost Reduction**

A. Direct Effect
↑ ICT adoption ⇒ Expand

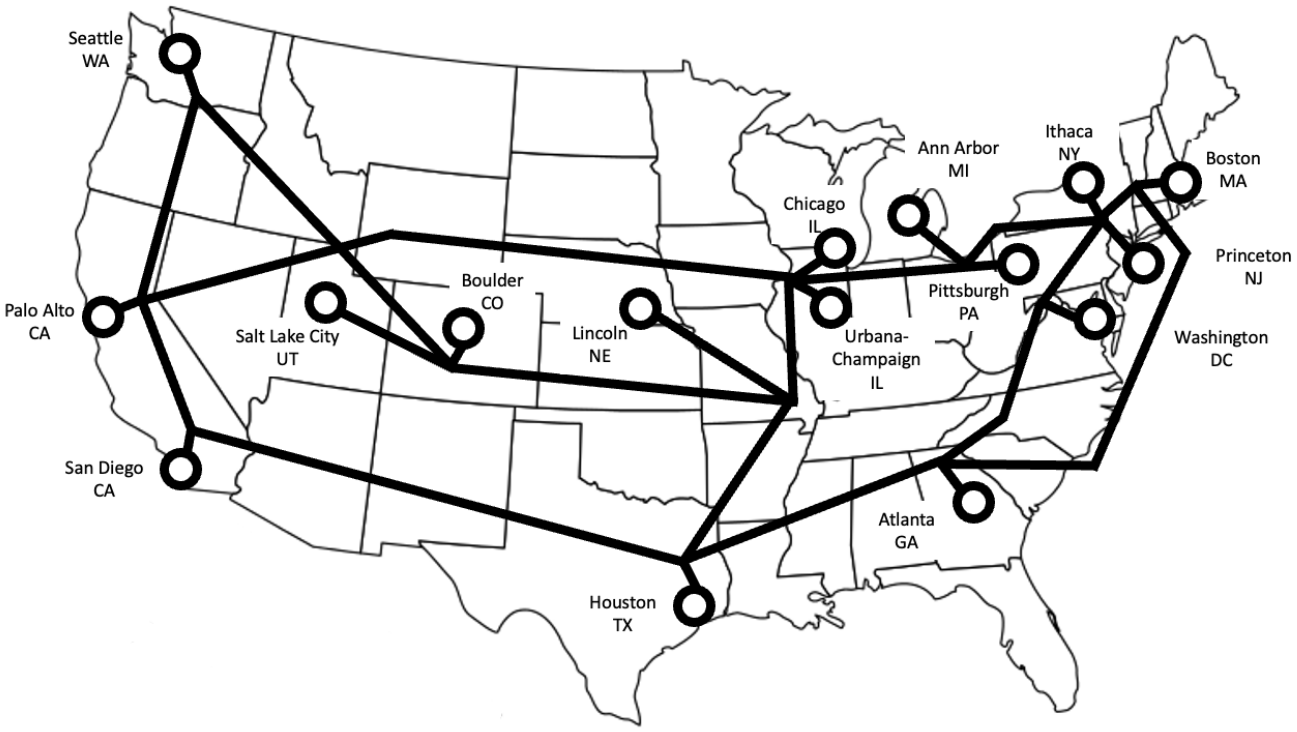


B. Indirect Effect
↑ Market competition ⇒ Contract



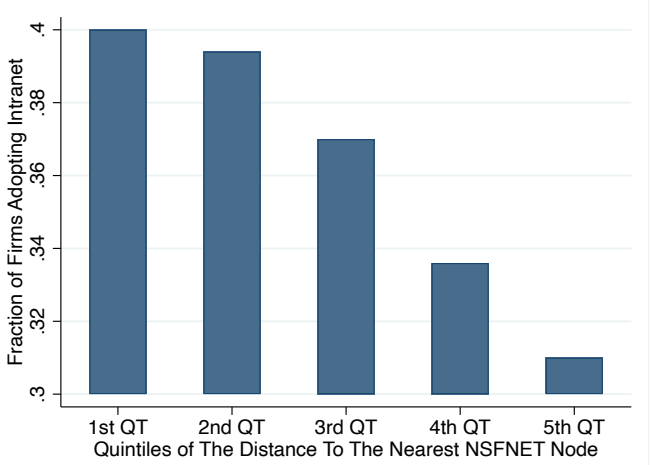
Notes: These figures plot the policy functions of location choices and ICT adoption against productivity in a simple example with three locations $\{HQ, L, H\}$ and for firms headquartered in HQ. Panel A plots the number of establishments and ICT adoption against productivity, with equilibrium prices held constant. The solid line corresponds to a high ICT cost, and the dotted line corresponds to a low ICT cost. The black fragment represents a low ICT level, and the red fragment represents a high ICT level. Panel B adds a dashed line that represents the policy function when prices are allowed to adjust endogenously.

Figure 5: **Map of NSFNET in 1992**



Notes: This figure shows the NSFNET backbones and its node sites in 1992. The circles represent the exterior nodes at the following cities: Princeton (NJ), San Diego (CA), Champaign (IL), Ithaca (NY), Pittsburgh (PA), Boulder (CO), Salt Lake City (UT), Palo Alto (CA), Seattle (WA), Lincoln (NE), Houston (TX), Ann Arbor (MI), College Park (MD), Atlanta (GA), Argonne (IL) and Cambridge (MA). The black lines represent traffic flows on the network.

Figure 6: **Relationship between Distance to NSFNET Node and Intranet Adoption in 1999**

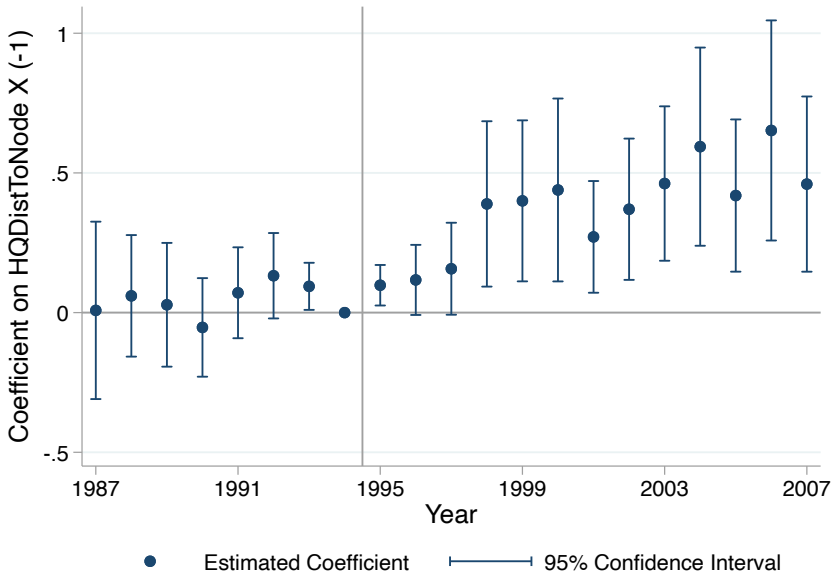


Notes: This figure shows the relationship between firms' likelihood of adopting an intranet and their distance to the nearest NSFNET node. Particularly, I estimate a regression of the form:

$$\text{Intranet}_i = \sum_{k=1}^{5} \beta_k \mathbb{1}[\text{HQDistToNode}_i \in k\text{'s Quintile}] + \text{CountyControls}_i \gamma + \alpha_i^{\text{Industry}} + \alpha_i^{\text{State}} + \varepsilon_i,$$

where k denotes the quintile and $\mathbb{1}[\text{HQDistToNode}_i \in k\text{'th quintile}]$ is an indicator set to one if firm i's distance belongs to the k's quintile in the distribution. CountyControls_i is a vector of county characteristics, including the logarithm of the county's population and median household income, share of population below the poverty line, share of black population, share of population above 65 years old, and share of population with bachelor's degree. $\alpha_i^{\text{Industry}}$ and α_i^{State} are the industry and state fixed effect, respectively. Each bar represents the coefficient β_k and is normalized by the fraction of firms adopting Intranet in the first quintile.

Figure 7: **Reduced-Form Effects of Internet Privatization**



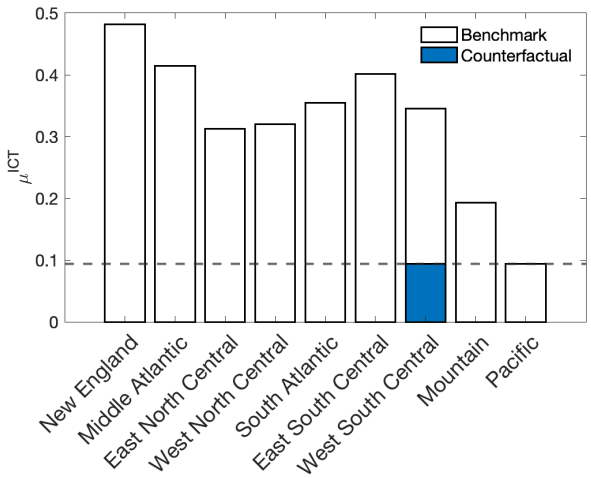
Notes: This figure shows the effect of the Internet privatization on firms' geographic span of control by estimating a regression of the form:

$$Y_{it} = \alpha_i + \beta_t \text{HQDistToNode}_i + \text{CountyControls}_i \gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

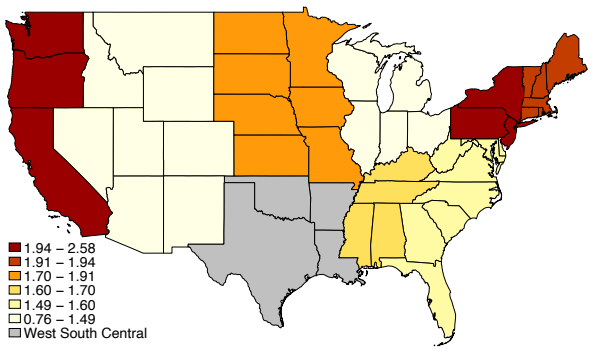
where the dependent variable is the number of establishments of firm i in year t and HQDistToNode_i is the distance from the firm's headquarters to the nearest NSFNET node. CountyControls_i is a vector of county characteristics, including the logarithm of the county's population and median household income, share of population below the poverty line, share of black population, share of population above 65 years old, and share of population with bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are the industry–year and state–year fixed effect, respectively. The regression is weighted by firms' employment share. Standard errors are clustered at the firm and county level.

Figure 8: **Unilateral ICT Cost Reduction: Changes in Expansion and Efficiency**

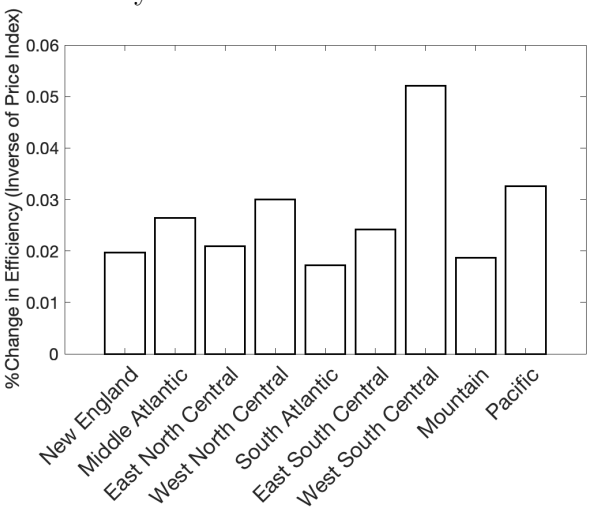
A. Logarithm of Average Fixed Costs of ICT



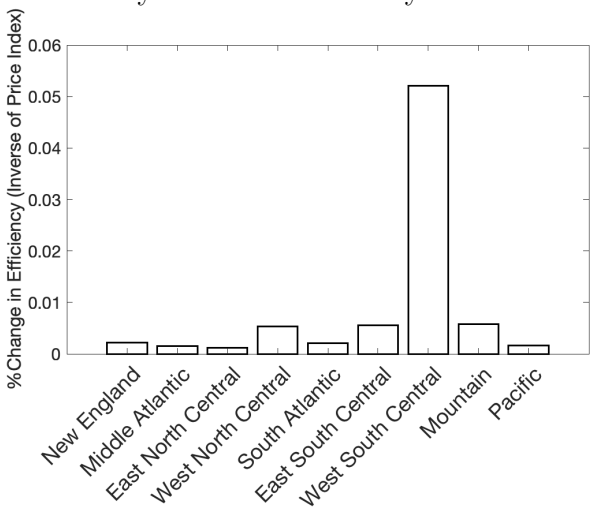
B. %Changes in Establishment Locations



C. Efficiency Gains: Benchmark Model



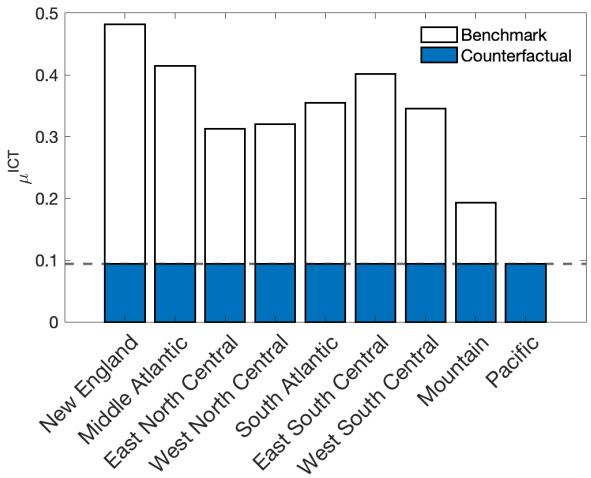
D. Efficiency Gains: Trade-Only Model



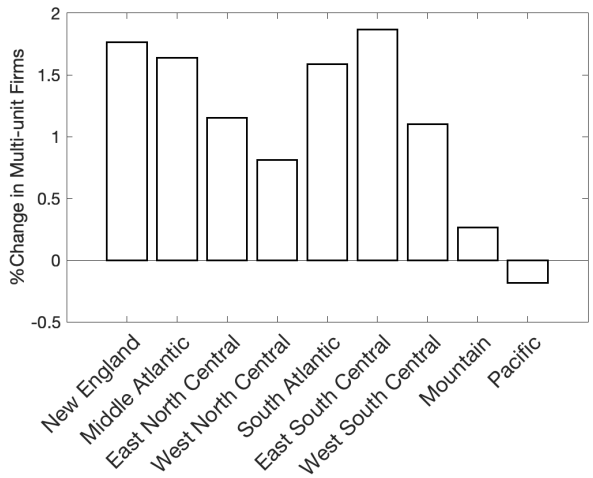
Notes: These figures show the changes for the policy simulation that reduces the fixed costs of ICT adoption in the West South Central census division. Panel A shows the logarithm of the average fixed costs of ICT adoption in each census division. Panel B shows the changes in the share of firms that expanded from the West South Central census division to the other census divisions. Panel C shows the local efficiency gains in the benchmark model, which includes both trade and multi-unit production. Panel D shows the local efficiency gains in a trade-only model, which shuts down the multi-unit production channel.

Figure 9: **Universal ICT Cost Reduction: Changes in Expansion and Efficiency**

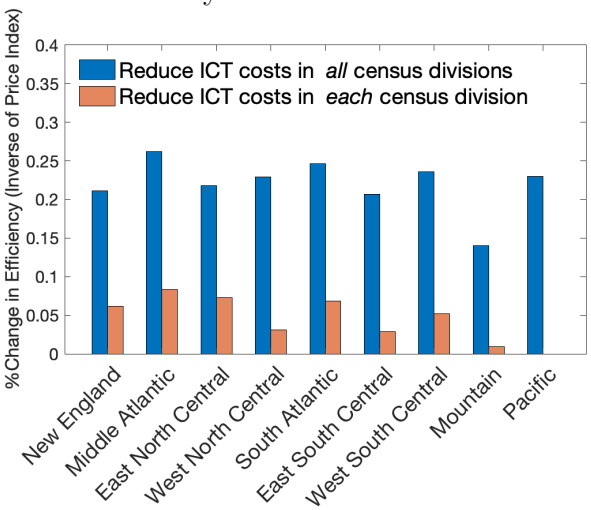
A. Logarithm of Average Fixed Costs of ICT



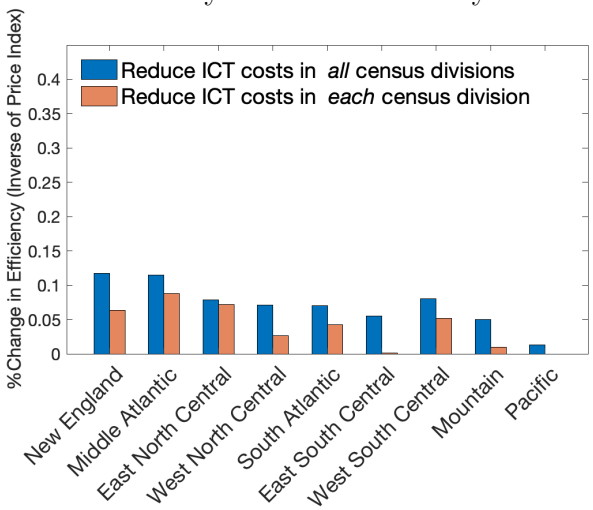
B. %Changes in Share of Multi-Unit Firms



C. Efficiency Gains: Benchmark Model



D. Efficiency Gains: Trade-Only Model



Notes: These figures show the changes with a reduction in the fixed costs of ICT adoption in all census divisions. Panel A shows the logarithm of the average fixed costs of ICT adoption in each census division. Panel B shows the changes in the share of multi-unit firms in each census division. Panel C shows the efficiency gains in the benchmark model, which includes both trade and multi-unit production, and compares the gains from an alternative policy that reduces the fixed costs of ICT adoption in each census division individually. Panel D compares the efficiency gains in a trade-only model, which shuts down the multi-unit production channel.

Table 1: **Summary Statistics**

	N	Mean	S.D.
A. 1977–2012 Longitudinal Business Database, Mfg., Census Years			
Employment	2,311,000	53.8	428.2
Payroll (in thousands)	2,311,000	1759	23690
Multi-unit firm	2,311,000	0.039	0.193
Number of establishments	2,311,000	1.105	1.205
B. 1999 Computer Network Use Supplement			
ICT Adoption			
Internet	18,500	0.726	0.446
Intranet	18,500	0.307	0.461
Electronic data interchange (EDI)	18,500	0.235	0.424
Extranet	18,500	0.070	0.254
Local area network (LAN)	18,500	0.641	0.480
Others	18,500	0.058	0.234
Communication			
Within Firm	18,500	0.338	0.473
Customers	18,500	0.294	0.456
Suppliers	18,500	0.533	0.499
Other Firm Characteristics			
Multi-unit firm	18,500	0.357	0.479
Number of establishments	18,500	2.317	4.262
Number of workers	18,500	322.6	1128
Number of production workers	18,500	239.0	853.8
Salary and wages (in thousands)	18,500	12790	59530
Production workers wages (in thousands)	18,500	8125	42520
Sales (in thousands)	18,500	103200	829800
Capital (in thousands)	18,500	41350	233100

Notes: This table shows summary statistics of firms in the manufacturing sector from the Longitudinal Business Database (LBD, in Panel A) and firms in the Computer Network Use Supplement (CNUS) to the 1999 Annual Survey of Manufactures (in Panel B). Each firm is a FIRMID×6-digit NAICS industry pair. Panel A presents summary statistics for the LBD sample with observations in census years from 1977 to 2012, i.e., years ending with 7 and 2. There are eight census years during this period. Panel B presents summary statistics for firms' ICT adoption, communication patterns, and other firm characteristics for the 1999 CNUS data. Multi-unit firm is an indicator set to one if a firm has more than one establishment. Each variable regarding ICT adoption is an indicator set to one if the firm is connected to a type of network. Variables regarding communication are indicators set to one if the firm communicates with other company units, external customers, and external suppliers, respectively. Sales is total value of shipments. Capital is book value of fixed assets at the end of the year.

Table 2: **Estimated Effects of Internet Privatization on Firms' Geographic Expansion**

A. Number of Establishments per Firm					
	Baseline	County Controls	Multi-unit Firms	IPW	Unweighted
	(1)	(2)	(3)	(4)	(5)
HQDistToNode × Post	-0.328***	-0.323***	-0.442**	-0.065***	-0.044**
	(0.098)	(0.097)	(0.191)	(0.023)	(0.017)
N	702000	702000	34500	702000	702000
Avg. Dep. Var	5.016	5.016	8.841	1.179	1.340
R^2	0.899	0.899	0.897	0.915	0.865
County controls		Y	Y	Y	Y
Industry-Year	Y	Y	Y	Y	Y
State-Year	Y	Y	Y	Y	Y

B. Alternative Measures of Firms' Geographic Span of Control					
Number of	Counties	States	Census Divisions	Out-of-State Establishments	Non-Drivable Establishments
	(1)	(2)	(3)	(4)	(5)
HQDistToNode×Post	-0.249***	-0.144***	-0.048**	-0.326***	-0.321***
	(0.082)	(0.044)	(0.019)	(0.092)	(0.090)
N	702000	702000	702000	702000	702000
Avg. Dep. Var	4.587	3.406	2.439	3.777	3.327
R^2	0.916	0.928	0.921	0.896	0.887
County controls	Y	Y	Y	Y	Y
Industry-Year	Y	Y	Y	Y	Y
State-Year	Y	Y	Y	Y	Y

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is a measure of the geographic span of control of firm i in year t, α_i is firm fixed effect, HQDistToNode_i is the distance from the ZIP code firm i is headquartered to its nearest NSFNET node (in 100 miles), and Post_t is an indicator set to one for years since 1995. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The dependent variable in Panel A is the number of establishments a firm operates. Column (1) reports the baseline results. Column (2) includes county characteristics as additional controls, including the logarithm of population and median household income, the share of black population and people over 65 years old, and the share of adults with bachelor's degrees. Column (3) restricts the sample to firms that are multi-unit throughout the sample period from 1987 to 2007. The regressions in column (1)–(3) are weighted by the firm's employment share. Column (4) reports the unweighted regression result. Column (5) reports the regression result weighted by the inverse propensity scores detailed in Appendix Section 10.2. Standard errors are clustered at the firm and headquarters county level.

In Panel B, the dependent variables for columns (1)–(3) are the number of counties, states, and census divisions where the firm has establishments. The dependent variable for columns (4)–(5) are the firm's number of establishments that are out of the headquarters state and that are nondrivable from the headquarters, i.e., establishments located over 250 miles away from the firm's headquarters. The regressions are weighted by the firm's employment share. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3: **Estimates of the Effect of ICT on Firms' Geographic Expansion**

	Intranet	Number of Establishments		
	First Stage	Reduced Form	IV	IV
	(1)	(2)	(3)	(4)
Intranet			1.235**	
			(0.531)	
HQDistToNode × Post	-0.035***	-0.043***		
	(0.009)	(0.014)		
AdvancedOnlineNetwork				1.264*
				(0.672)
N	58000	58000	58000	58000
Avg. Dep. Var	0.036	1.326	1.326	1.326
F-stat			15.27	7.221
County Controls	Y	Y	Y	Y
Industry-Year FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y

Notes: This table uses the balanced panel from 1987 to 1999 to estimate the effect of intranet adoption on firms' geographic span of control. Column (1) estimates the regression

$$\text{Intranet}_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is a time-varying variable of a firm's intranet status that interacts the firm's intranet adoption status in 1999 and a postprivatization indicator, α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years since 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, the share of black population and people over 65 years old, and the share of adults with bachelor's degrees. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. Column (2) estimates a regression of the same form as that from column (1) but replaces the dependent variable with the number of establishments of firm i in year t, i.e., Y_{it}. Column (3) estimates regressions of the form:

$$Y_{it} = \alpha_i + \gamma \widehat{\text{Intranet}}_{it} + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is the number of establishment of firm i in year t and $\widehat{\text{Intranet}}_{it}$ is the predicted values generated by the first-stage regression in column (1). Column (4) estimates the regression of the same form as that from column (3) but replaces the predicted values of Intranet by those of AdvancedOnlineNetwork, which is an indicator set to one if a firm adopted any of the advanced online networks including Intranet, Extranet, and Electronic data interchange (EDI). The regressions are weighted by the inverse propensity scores. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: **Summary of Parameters**

Parameter	Description	Value	Estimation Strategy
A. Assigned Parameters			
σ	Demand elasticity	4	
θ	Dispersion of local productivity	3.6	
μ^z	Mean of log firm productivity (Guner et al., 2008)	-0.123	
σ^z	Dispersion of log firm productivity (Guner et al., 2008)	0.767	
$\overline{h}$	Firm-wide communication costs with high ICT	1	
β^τ	Elasticity of trade costs w.r.t. distance (Disdier and Head, 2008)	0.278	
B. Estimated Parameters			
$\beta^d_{\text{Low ICT}}$	Elasticity of communication costs w.r.t distance with low ICT	0.181	Step 1: Estimate within-firm gravity equation
$\beta^d_{\text{High ICT}}$	Elasticity of communication costs w.r.t distance with high ICT	0.072	Step 1: Estimate within-firm gravity equation
T	Mean of local productivity for each location	Table 18	Step 2: Decompose location fixed effects
$\underline{h}$	Firm-wide communication costs with low ICT	1.335	Step 3: Method of simulated moments
β^X_1	Intercept of avg. fixed costs of setting up establishments	1.733	Step 3: Method of simulated moments
β^X_2	Elasticity of avg. fixed costs of setting up establishments w.r.t distance	0.073	Step 3: Method of simulated moments
σ^X	Dispersion of fixed costs of setting up establishments	2.878	Step 3: Method of simulated moments
β^{ICT}_1	Intercept of avg. fixed costs of adopting ICT	1.289	Step 3: Method of simulated moments
β^{ICT}_2	Elasticity of avg. fixed costs of adopting ICT w.r.t. DistToNode	0.121	Step 3: Method of simulated moments
σ^{ICT}	Dispersion of fixed costs of adopting ICT	4.061	Step 3: Method of simulated moments

Notes: This table summarizes the model parameters. Panel A displays the parameters that are assigned (i.e., those not estimated). Panel B displays the parameters that are estimated.

Table 5: **First-Step Estimation Results**

	Establishment Employment Share			
	All Years	Year 1999		
	(1)	(2)	(3)	(4)
Log(Miles)	-0.172***	-0.293**	-0.652**	-1.202***
	(0.047)	(0.137)	(0.199)	(0.387)
Log(Miles) × Intranet			0.394**	0.997**
			(0.167)	(0.401)
N	59500	3100	3100	3100
Market Access	Y	Y	Y	Y
HQ-Set-ICT FE	Y	Y	Y	Y
Establishment Location FE		Y	Y	Y
Industry FE		Y	Y	Y
Establishment Location-Year FE	Y			
Industry-Year FE	Y			
Instrumental Variable				Y

Notes: This table presents the first-step estimation results. The dependent variable is the scaled within-firm employment shares of establishments. Log(Miles) is the distance between the firm's headquarters and the establishment. Column (1) uses the LBD–CNUS matched sample from 1987 to 2007. Columns (2)–(4) use the 1999 subsample of the matched sample. Standard errors are clustered at the firm level. Standard errors using the instrumental variable approach in column (4) are calculated by 1,000 bootstrapped samples. The regressions are weighted by the weights provided in the 1999 Annual Survey of Manufactures. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: **Second-Step Regression Results**

	Purified Estimates of Census Division Fixed Effect		
	(1)	(2)	(3)
Log(R&D stock)	0.741***		0.635***
	(0.126)		(0.106)
Log(Market access)		0.887***	0.743**
		(0.255)	(0.225)
N	189	189	189
R^2	0.966	0.965	0.972
Census Division FE	Y	Y	Y
Year FE	Y	Y	Y

Notes: The dependent variable is the census division fixed effect from 1987 to 2007 that is estimated in the first-stage regression and purged of local wages. The independent variables include the logarithm of R&D stocks and the logarithm of market access. R&D stocks are constructed by the perpetual inventory method using industrial R&D expenditure at the state level and aggregated to the census division level. Market access is approximated by the average trade cost weighted by demand from each destination market. All regressions include the census fixed effect and year fixed effect. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 7: **Data and Model-Simulated Moments**

Moment	Data	Model
A. Expansion Patterns		
Share of multi-unit firms	0.343	0.343
Share of multi-unit firms with employment below median	0.020	0.025
Corr(%Firms$_{os}$, Log(Miles$_{os}$))	-0.369	-0.369
B. ICT Adoption Patterns		
Share of firms adopting Intranet	0.367	0.361
Share of firms adopting Intranet with employment below median	0.048	0.062
Corr(Intranet, Log($\widetilde{\text{HQDistToNode}}_o$))	-0.028	-0.029
C. Correlation of ICT Adoption and Multi-Unit Production		
Corr(Intranet, Multi-Unit)	0.555	0.559

Notes: This table compares the model simulated moments to data moments. Panel A includes moments that summarize firms' expansion patterns: the overall share of multi-unit firms, the share of multi-unit firms with employment below the median, and the correlation of the share of firms expanding from one census division to another and the logarithm of the distance (in miles) between the two census divisions. Panel B includes moments that summarize firms' ICT adoption patterns: the overall share of firms that have adopted an intranet, the share of adopting firms with employment below the median, and the correlation between a firm's ICT adoption and the logarithm of average distance to the nearest NSFNET node in the firm's headquarters census division, which is scaled by the census division's land area. Panel C is the correlation between a firm's intranet adoption and multi-unit status.

Table 8: **Third-Step Parameter Estimates**

	β_1^X	β_2^X	σ^X	$\underline{h}$	β_1^{ICT}	β_2^{ICT}	σ^{ICT}
Estimate	1.733	0.073	2.878	1.335	1.289	0.121	4.061
S.E.	(0.304)	(0.046)	(0.146)	(0.172)	(0.976)	(0.082)	(0.646)

Notes: This table reports the estimates from the third-step estimation using method of simulated moments. Standard errors are reported in the parentheses.

Table 9: **Efficiency Gains from Internet Privatization**

%Change in	Reduced Form (1)	Model: Partial Equilibrium (2)	Model: General Equilibrium (3)
Average Number of Census Divisions per Firm	2.56	2.56	1.71
National Average Efficiency (Endogenous Locations)	–	–	1.29
National Average Efficiency (Fixed Locations)	–	–	0.80

Notes: This table shows the changes in firm geographic span of control and efficiency from the Internet privatization. Column (1) reports the reduced-form estimate. Column (2) shows the simulated changes with fixed prices. Column (3) shows the simulated changes in the benchmark model with endogenous prices.

Table 10: **Decomposition of Efficiency Gains from Internet Privatization**

	%Change in Efficiency	Decomposition (%)				
		Outside Firms				Local Firms
		Stayers	Entrants	Exiters	Never-Comers	
	(1)	(2)	(3)	(4)	(5)	(6)
New England	1.23	17	53	-7	21	17
Middle Atlantic	1.04	13	34	-4	34	23
East North Central	1.41	19	39	-5	4	43
West North Central	1.36	49	22	-3	16	15
South Atlantic	1.35	64	17	-12	5	25
East South Central	1.42	58	24	-6	14	10
West South Central	0.93	33	24	-7	35	14
Mountain	1.41	58	26	-8	14	9
Pacific	1.47	31	56	-6	3	16
National Average	1.29	38	33	-6	16	19

Notes: This table decomposes the efficiency gains in each location to contributions from different types of firms. The efficiency gain is calculated as the change in the local price index. Column (1) shows the local efficiency gains in each census division. Columns (2)–(5) report the contribution to local efficiency gains from different outside firms, as described in Section 6. Column (6) reports the contribution from local firms that are headquartered in each location.

Online Appendix: Not for Publication

Appendix A describes additional details of the data and variable construction. Appendix B documents the institutional background and robustness checks for the reduced form analysis. Appendix C provides details of the model derivation. Appendix D and E provide additional information for the structural estimation and policy simulation, respectively.

9 Data Appendix

9.1 Identifying Firm Headquarters

This appendix section outlines the procedure to identify firms' headquarters and their locations and employment. Firms can be categorized into three types: 1) single-unit firms, 2) multi-unit firms with stand-alone headquarters, and 3) multi-unit firms with integrated headquarters. As single-unit firms have only one establishment, that establishment is considered the headquarters. I obtain the location and employment of these single-unit firms' headquarters from the Longitudinal Business Database (LBD).

For the second type of firm, I augment the LBD with the Census of Auxiliary Establishments (AUX) to identify the stand-alone headquarters of multi-unit firms. According to the Census Bureau, auxiliary establishments do not engage in production but rather in management, supervision, general administrative functions, and supporting services for other establishments of the same enterprise, serving, for example, as corporate headquarters, R&D and testing laboratories, warehouses and so forth. The AUX is collected every five years (census years that end in 2 and 7). I use the firm's headquarters locations at the beginning of the sample period in 1987 to construct the firm's distance to the nearest NSFNET node. I follow the procedure in Aarland et al. (2007) and Giroud (2013) to identify these stand-alone headquarters of multi-unit firms. The 1987 AUX provides a detailed breakdown of employment of administrative and managerial employees, office and clerical employees, R&D and testing employees, warehousing employees, sales employees, and so forth. An establishment is identified as a headquarters if its total employment in administrative, managerial, and clerical work is larger than its employment in any of the other types of work. While many firms have one headquarters identified using this criterion, some firms have multiple establishments identified as their headquarters.[54] In this case, I use the Standard Statistical Establishment Listing (SSEL) to obtain the establishment's name and consider an establishment the headquarters if its name includes the word "headquarters." After these two rounds of selection, if a firm still has multiple headquarters identified, I choose the one with the largest payroll as the headquarters. The salaries are often higher for employees engaging in management, e.g., executives.

[54]Since 1997, headquarters have been classified with NAICS code 551114.

The third type of firm is multi-unit firms that integrate their headquarters with manufacturing units. Similarly, I choose the establishment with the largest payroll as the headquarters for these multi-unit firms.

9.2 Decomposing Firms' Span of Control

To disentangle firms' geographic span of control from their industry scope, I decompose the average number of establishments belonging to the same FIRMID into two components—one reflecting the average number of industries in which a firm operates (i.e., its industrial span of control) and the other reflecting the average number of establishments that a firm owns within an industry (i.e., its within-industry geographic span of control).

Denote firm at the FIRMID level by i. Let N_i^{est} and N_i^{ind} denote the number of establishments and the number of industries that firm i operates, respectively. Denote the industry by j. Let N_{ij}^{est} denote the number of establishments that firm i owns in industry j. Then, we can decompose the average number of establishments per firm into the firm's industry scope and within-industry geographic span of control:

$$\overbrace{\frac{\sum_{i=1}^{N^{\text{firm}}} N_i^{\text{est}}}{N^{\text{firm}}}}^{\text{avg. number of establishments per FIRMID}} = \frac{\sum_{i=1}^{N^{\text{firm}}} N_i^{\text{est}}}{\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}} \frac{\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}}{N^{\text{firm}}}$$

$$= \underbrace{\frac{\sum_{i=1}^{N^{\text{firm}}} \sum_{j=1}^{N_i^{\text{ind}}} N_{ij}^{\text{est}}}{\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}}}_{\substack{\text{avg. number of establishments} \\ \text{per FIRMID–industry}}} \underbrace{\frac{\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}}{N^{\text{firm}}}}_{\substack{\text{avg. number of industries} \\ \text{per FIRMID}}} \equiv \frac{\sum_{\tilde{i}=1}^{\tilde{N}^{\text{firm}}} N_{\tilde{i}}^{\text{est}}}{\tilde{N}^{\text{firm}}} \frac{\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}}{N^{\text{firm}}}.$$

I add a term $\sum_{i=1}^{\text{firm}} N_i^{\text{ind}}$ to both the denominator and numerator in the first equality. The second equality follows that $N_i^{\text{est}} = \sum_{j=1}^{N_i^{\text{ind}}} N_{ij}^{\text{est}}$; that is, the number of establishments that a firm owns equals the total number of establishments in each industry that the firm operates. Now, define a firm by a FIRMID–industry pair, and denote the firm $\tilde{i}$, i.e., $\tilde{i} = (i, j)$. Let $\tilde{N}^{\text{firm}}$ denote the number of firms at the FIRMID–industry level. Then, we can obtain that $\sum_{i=1}^{\text{firm}} \sum_{j=1}^{N_i^{\text{ind}}} N_{ij}^{\text{est}} = \sum_{\tilde{i}=1}^{\tilde{N}^{\text{firm}}} N_{\tilde{i}}^{est}$ and $\sum_{i=1}^{\text{firm}} N_i^{\text{ind}} = \tilde{N}^{\text{firm}}$, leading to the last equality.

To focus on the role of ICT in firms' within-industry expansion across locations, I define a firm by a FIRMID–industry pair, where the industry is at the six-digit NAICS level. To offer a contrast with the span of control from the industry scope perspective, Figure 11 plots the average number of industries and establishments for manufacturing firms that operate in either multiple locations or multiple industries, where the industry is at the six-digit NAICS level. The average number of industries per firm, in contrast to the average number of establishments per firm, decreased over time. Combined with the within-industry geographic expansion, the overall

number of establishments belonging to the same FIRMID declined in the 1980s, driven by the decreasing number of industries, and then rose from the late 1990s, driven by the increasing number of establishments within industries, i.e., geographic expansion.

10 Reduced-Form Analysis Appendix

10.1 National Science Foundation Network

This appendix section provides a brief history of NSFNET from its initiation in 1986 to its ultimate privatization in 1995.

1986-1991: Expansion and Upgrade

The National Science Foundation Network was initiated in 1986, linking the National Center for Atmospheric Research in Boulder, Colorado, and five NSF-sponsored supercomputing centers: the John von Neumann Center in Princeton, New Jersey; the San Diego Supercomputer Center in San Diego, California; the National Center for Supercomputing Applications in Urbana, Illinois; the Cornell Theory Center in Ithaca, New York; and the Pittsburgh Supercomputing Center in Pittsburgh, Pennsylvania. The Internet speed was at 56 Kbit per second, providing a fast connection across the six NSFNET node sites.

During its first two years of operation, NSFNET experienced its first round of upgrades and expansion. The network was expanded to thirteen nodes, with the seven new nodes located in Salt Lake City, Utah; Palo Alto, California; Seattle, Washington; Lincoln, Nebraska; Houston, Texas; Ann Arbor, Michigan; and College Park, Maryland. Its speed increased to 1.5 Mbit per second (making it a so-called T1 network).[55] Moreover, NSFNET provided connections to the backbone nodes from regional networks; these regional networks were in turn connected to smaller regional and campus networks.

From 1990, NSFNET saw its second round of upgrades and expansion. By the end of 1991, the network had added three more nodes: one in Atlanta, Georgia; another at Argonne National Laboratory in Lemont, Illinois; and another in Cambridge, Massachusetts. Its speed increased to 45 Mbit per second (making it a so-called T3 network). The core backbone equipment was moved to MCI's junction places to ensure robust infrastructure and stable power.

1991–1995: Commercialization and Privatization

The goal of NSFNET was to facilitate communication, collaboration and information sharing among higher education and research institutes. Commercial usage was restricted by the *Accept-*

[55]The NSF partnered with Merit Network, a consortium of Michigan universities, and industry players including IBM and MCI. In the upgrade and expansion process, IBM provided hardware and software support, and MCI provided fiber-optic circuits at a reduced rate.

able Use Policy. With exploding interest and demand from the commercial side, however, these restrictions were gradually lifted.

In March 1991, the *Acceptable Use Policy* was revised to allow NSFNET to carry commercial Internet traffic. The Scientific and Advanced Technology Act of 1992 formally authorized the NSF "to foster and support access by the research and education communities to computer networks which may be used substantially for additional purposes if this will tend to increase the networks' overall capabilities."[56] In the spring of 1993, the NSF released a solicitation to the private sector and transitioned to a new Internet architecture; the awards were announced in 1994.[57]

While attempts to commercialize the Internet started in the early 1990s, the "Internet gold rush" did not arrive until the last moment, when the NSFNET backbone was decommissioned in April 1995. The final restrictions on commercial Internet use were lifted. Together with business successes at the time, privatization catalyzed the explosive development of the Internet and related industries. Figure 13, adapted from Table 5.1 in Greenstein (2015), shows the number of Internet service providers listed in *Boardwatch Magazine* during 1993–1998.[58] The number slightly increased from 24 in November 1993 to 35 in January 1995 but jumped to over 2,000 by May 1996, reflecting the rapid development of commercial Internet access that followed the Internet privatization.

Advanced Research Projects Agency Network

NSFNET was closely related to its predecessor, ARPANET, funded by the Department of Defense since the 1960s. Following ARPANET, NSFNET used packet-switching technology and the TCP/IP protocol.[59] The node locations of NSFNET were also influenced by ARPANET, whose nodes were mostly located within military bases, federal agencies and university computer science departments. Therefore, the locations of NSFNET nodes were less likely to have been subject to contemporaneous local shocks at the time of the Internet privatization.

10.2 General Propensity Score

This appendix section provides details on the generalized propensity score reweighting in the robustness checks. I construct the generalized propensity score of treatment, using firm and location characteristics before the Internet privatization, and apply the inverse propensity score method to reweight observations for the difference-in-differences regression.

[56] Scientific and Advanced-Technology Act of 1992, S.1146.

[57] Frazer (1996) documents the details of the new network architecture and award winners.

[58] *Boardwatch Magazine* was initially a journal for bulletin board systems. From the late 1990s, it became a magazine for the Internet service providers.

[59] In a packet-switching network, data delivered from a source device are broken into packets and reassembled at the target device. The Transmission Control Protocol (TCP) and the Internet Protocol (IP) ensure that these packets reach the target device and are reassembled in the right order.

Denote the firm by i and its covariates by X_i; the generalized propensity score is defined as the conditional distribution of the treatment, i.e., $f_{D|X}$, where the treatment is the distance to the nearest NSFNET node. I assume that conditional on the covariates, the treatment is log-normally distributed with the mean as a function of the covariates; that is,

$$\text{HQDistToNode}_i \mid X_i \sim \log N(X_i\beta, \sigma^2). \tag{22}$$

The covariates X_i are comprised of two components: One is a vector of firm-specific characteristics, including the firm's number of establishments and the logarithm of employment. The other is a vector of county-specific characteristics, including the logarithm of local population, logarithm of median household income, share of population below the poverty line, share of people over sixty-five years old, share of the black population, and share of the population with a bachelor's degree and above. I also include the one-year growth rate in these covariates and a full set of state dummies. The conditional distribution of treatment is

$$\begin{aligned} &f_{\text{D}|X}(\text{HQDistToNode}_i \mid X_i) \\ &\quad = \frac{1}{\text{HQDistToNode}_i\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\log \text{HQDistToNode}_i - X_i\beta)^2}{2\sigma^2}\right). \end{aligned} \tag{23}$$

Then, we can define the weight as $w_i = f_{\text{D}}/f_{\text{D}|X}$, where the numerator is a required stabilizing factor equal to the marginal distribution of treatment and the denominator is the generalized propensity score defined above (see Robins et al., 2000). I follow the common approach and assume the marginal distribution to be log-normal; that is, $\text{HQDistToNode}_i \sim \log N(\overline{\mu}, \overline{\sigma})$. Therefore, the weight is given by

$$w_i = \frac{\sigma}{\overline{\sigma}} \exp\left(\frac{(\log \text{HQDistToNode}_i - X_i\beta)^2}{2\sigma^2} - \frac{(\log \text{HQDistToNode}_i - \overline{\mu}))^2}{2\overline{\sigma}^2}\right). \tag{24}$$

I use observations at the beginning of the sample period in 1987 to estimate the parameters (β, σ, $\overline{\mu}$, $\overline{\sigma}$) via the maximum likelihood estimator. To show that the distance measure is not correlated with firm and location characteristics before the privatization, I regress the distance on those covariates using the 1987 observations and adjust the regression by the weights specified in Equation (24):

$$\text{HQDistToNode}_i = \alpha + X_i\beta + \alpha_i^{\text{Industry}} + \alpha_i^{\text{State}} + u_i. \tag{25}$$

As industries might cluster in certain regions, I include the industry fixed effect at the 4-digit NAICS level. To account for heterogeneity across states, I include the state fixed effect. Standard errors are clustered at the county level. Figure 14 plots the coefficients. These estimated coefficients are economically small and statistically insignificant, indicating that, after reweighting, the

distance measure is not systematically correlated with firm and location characteristics before the Internet privatization.

10.3 Heterogeneous Effects by Distance Bin

I test the heterogeneity in the effect of the Internet privatization at different ranges of distance to NSFNET nodes. I perform the test by grouping firms into ten equal-size bins according to their distance to nodes (i.e., HQDistToNode) and estimating the following regression:

$$Y_{it,k} = \alpha_i + \sum_{k=1}^{10} \beta_k \text{HQDistToNode}_i \times \text{Post}_t + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it,k}, \tag{26}$$

where $Y_{it,k}$ is the number of establishments of firm i in year t and k indicates that firm i belongs to the kth distance bin. Panel A of Figure 15 plots the estimated coefficient $\hat{\beta}_k$ for each distance bin. All estimates are negative, indicating that within any distance bin, firms headquartered closer to nodes increase their number of establishments. To interpret the magnitude of these estimates, I calculate the effect of the Internet privatization by $\text{Effect}_k = \beta_k \times \overline{\text{HQDistToNode}}_k$, where $\overline{\text{HQDistToNode}}_k$ is the average distance for distance bin $k = 1, \cdots, 10$. Panel B plots these estimated effects, which range from 0.25 to 1.79. Moreover, the effect is larger for firms headquartered far away from the nodes.

10.4 Intensive-Margin Effects

To highlight firms' expansion at the extensive margin, i.e., their geographic expansion, I compare it to their overall expansion and expansion at the intensive margin, such as in employment. Table 15 reports the difference-in-differences estimates of the effect of the Internet privatization on firms' employment, employment per establishment, and wage rate. In line with the estimates for geographic expansion, the estimate for firm total employment is negative and statistically significant at the 10% level, indicating that the privatization increased firms' overall size. However, the privatization did not have significant effects on establishment size or wages.

10.5 Location of New Establishments

I test whether firms close to nodes are more likely to set up establishments also close to the nodes. I run the baseline difference-in-differences regression using the average distance from firms' *new establishments* to the nearest NSFNET nodes as the dependent variable. As shown in column (1) of Table 16, the estimated coefficient is positive and statistically significant, indicating that firms headquartered in locations *closer* to nodes—those with better access to ICT—also build new establishments *closer* to the nodes. This is consistent with our premise that interlocutors

at both ends of the communication channel need access to ICT. The distance to nodes, however, might be correlated with other location characteristics. Columns (2)–(7) of Table 16 show the results with the average county characteristics of new establishments as dependent variables. For instance, column (2) shows that firms headquartered closer to nodes tend to set up establishments in counties with larger populations, but the difference is not statistically distinguishable from zero. Overall, these results suggest that firms with better access to the Internet tend to locate new establishments in counties with higher household income and younger populations and with smaller distances to nodes.

11 Model Appendix

11.1 The Consumer's Problem

Denote the firm by i and its headquarters location by o. As each firm produces a continuum of varieties ω, each product can be denoted by a firm–variety combination (i, ω). Denote the consumer's location by k, aggregate consumption by Y_k, and the expenditure by E_k. Denote the price index by P_k such that $E_k = P_k Y_k$. In each location, given the product prices (i.e., $p_{ok}(i,\omega)$) and total expenditure (i.e., E_k), the representative consumer maximizes her utility that aggregates all varieties with constant elasticity of substitution σ. We can express the consumer's problem as follows: in each location k,

$$\max_{\{y_{ok}(i,\omega)\}_{\omega,i,o}} \left(\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}} d\omega di \right)^{\frac{\sigma}{\sigma-1}},$$

subject to the budget constraint $\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 p_{ok}(i,\omega) y_{ok}(i,\omega) d\omega di \leq E_k$. The Lagrangian is

$$\mathscr{L} = \left(\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}} d\omega di \right)^{\frac{\sigma}{\sigma-1}} + \mu \left[E_k - \sum_{o=1}^{N} \int_0^{m_o} \int_0^1 p_{ok}(i,\omega) y_{ok}(i,\omega) d\omega di \right]$$

The first-order condition for each product is

$$Y_k^{-1/\sigma} y_{ok}(i,\omega)^{-1/\sigma} = \mu p_{ok}(i,\omega), \tag{27}$$

where $Y_k \equiv \left(\sum_{o=1}^{N} \int_0^{m_o} \int_0^1 y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}} d\omega di \right)^{\frac{\sigma}{\sigma-1}}$. Then, we can express the expenditure on any product by the price and quantity of product ω of firm i headquartered in location o; that is,

$p_{ok}(i',\omega')y_{ok}(i',\omega') = p_{ok}(i,\omega)y_{ok}(i,\omega)^{1/\sigma}y_{ok}(i',\omega')^{(\sigma-1)/\sigma}$. Thus, the total expenditure is

$$\begin{aligned}
&\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 p_{ok}(i',\omega')y_{ok}(i',\omega')d\omega di \\
=&\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 p_{ok}(i,\omega)y_{ok}(i,\omega)^{\frac{1}{\sigma}}y_{ok}(i',\omega')^{\frac{\sigma-1}{\sigma}}d\omega di \\
=&p_{ok}(i,\omega)y_{ok}(i,\omega)^{\frac{1}{\sigma}}Y_k^{\frac{\sigma-1}{\sigma}} = E_k, \qquad (28)
\end{aligned}$$

where the last equality follows the budget constraint. By definition of the price index, we can derive the demand for each product from location k:

$$y_{ok}(i,\omega) = E_k P_k^{\sigma-1}p_{ok}(i,\omega)^{-\sigma}. \qquad (29)$$

Integrating $y_{ok}(i,\omega)^{\frac{\sigma-1}{\sigma}}$ over (i,ω) and summing over the headquarters location o, we can get the price index for each location k: $P_k = \left(\sum_{o=1}^{N}\int_0^{m_o}\int_0^1 p_{ok}(i,\omega)^{1-\sigma}\right)^{1/(1-\sigma)}$.

11.2 The Firm's Problem Given Its Set of Locations and ICT

This appendix section provides more details on the derivation of the firm's sales, given a set of establishment locations and the state of its ICT.

Let o denote the firm's headquarters location, z the firm-specific productivity, S the set of establishment locations in which the firm operates, and φ the ICT level. As the production function has constant returns to scale and uses labor as the only input, the firm's unit cost of producing a variety ω at its establishment in location s and shipping to market k is $c_{oks}(\omega,\varphi,z) = (z\varepsilon_s(\omega))^{-1}w_s\tau_{sk}\gamma_{os}(\varphi)$, where $\varepsilon_s(\omega)$ is establishment-specific productivity, which follows a Fréchet distribution and is independently and identically distributed across locations and varieties; w_s is the wage rate in location s; τ_{sk} is the shipping cost between location s and market k; and $\gamma_{os}(\varphi)$ is the communication cost between headquarters location o and establishment location s.

In each market exists a representative consumer who makes consumption decisions independently. Due to the constant-returns-to-scale production function at the establishment level, the firm chooses the establishment with the lowest unit cost to serve each market. That is, for any variety $\omega \in [0,1]$, the actual cost to market k is $c_{ok}(\omega,S,\varphi,z) = \min_{s\in S} c_{oks}(\omega,\varphi,z)$. Let variety $\omega \in [0,1]$ be given. Since establishment productivity $\varepsilon_s(\omega)$ follows a Fréchet distribution with scale parameter T_s and shape parameter θ and is i.i.d. across locations, we can derive the distribution

of the lowest unit cost for market k:

$$\begin{aligned}
P(c_{ok}(\omega,S,\varphi,z)\leq c) &= 1-P(c_{ok}(\omega,S,\varphi,z)>c) = 1-P(\min_{s\in S} c_{oks}(\omega,\varphi,z)>c)\\
&= 1-\prod_{s\in S} P(c_{oks}(\omega,\varphi,z)>c) = 1-\prod_{s\in S} P((z\varepsilon_s(\omega))^{-1}w_s\tau_{sk}\gamma_{os}(\varphi)>c)\\
&= 1-\prod_{s\in S} P(\varepsilon_s(\omega)<(cz)^{-1}w_s\tau_{sk}\gamma_{os}(\varphi)) = 1-\prod_{s\in S} e^{-\left((cz)^{-1}T_s^{-1}w_s\tau_{sk}\gamma_{os}(\varphi)\right)^{-\theta}}\\
&= 1-e^{-c^\theta z^\theta \sum_{s\in S} T_s^\theta (w_s\tau_{sk}\gamma_{os}(\varphi))^{-\theta}} \equiv 1-e^{-c^\theta z^\theta \Phi_{ok}(S,\varphi)},
\end{aligned}$$

where we define $\Phi_{ok}(S,\varphi)\equiv\sum_{s\in S} T_s^\theta\left(w_s\tau_{sk}\gamma_{os}(\varphi)\right)^{-\theta}$ as the "production potential" of the firm to market k, which summarizes the states of technology, input costs, market access, and costs of communication with the headquarters of all the establishment locations.

As the demand has constant elasticity of substitution, the firm charges a constant markup over the marginal cost, which is the same as the unit cost in this case, with a factor of $\sigma/(\sigma-1)$. Thus, the distribution of the price of variety ω that the firm charges in market k (i.e., $p_{ok}(\omega,S,\varphi,z)$) has the cumulative distribution function of

$$P(p_{ok}(\omega,S,\varphi,z)\leq p) = 1-e^{-\left(\frac{\sigma-1}{\sigma}\right)^\theta c^\theta z^\theta \Phi_{ok}(S,\varphi)}. \tag{30}$$

By the demand function in Equation (29), the sales of variety ω of the firm to market k is

$$\text{sales}_{ok}(\omega,S,\varphi,z) = p_{ok}(\omega,S,\varphi,z)y_{ok}(\omega,S,\varphi,z) = E_k P_k^{\sigma-1} p_{ok}(i,\omega)^{1-\sigma}, \forall\omega\in[0,1] \tag{31}$$

Therefore, the total sales of the firm to market k is

$$\begin{aligned}
\text{sales}_{ok}(S,\varphi,z) &= E_k P_k^{\sigma-1}\int_0^1 p_{ok}(i,\omega)^{1-\sigma}d\omega\\
&= \Gamma\left(\frac{\theta-\sigma+1}{\theta}\right)\left(\frac{\sigma-1}{\sigma}\right)^{\sigma-1} z^{\sigma-1}E_k P_k^{\sigma-1}\Phi_{ok}(S,\varphi)^{\frac{\sigma-1}{\theta}},
\end{aligned} \tag{32}$$

where E_k is the consumer's expenditure and P_k is the ideal price index in location k. Here, it is required that $\frac{\theta-\sigma+1}{\theta}>0$ to have a proper definition. It is worthwhile to note that the share of sales to market k that is generated from the establishment in location $s\in S$ equals the share of varieties that have the lowest unit costs in location s. That is,

$$\zeta_{ok\leftarrow s} \equiv \frac{\text{sales}_{ok\leftarrow s}(S,\varphi,z)}{\text{sales}_{ok}(S,\varphi,z)} = \frac{T_s^\theta(\gamma_{os}(\varphi)w_s\tau_{sk})^{-\theta}}{\Phi_{ok}(S,\varphi)}. \tag{33}$$

11.3 Within-Firm Gravity Equation

Denote the firm's productivity by z, its headquarters location by o, the set of its establishment locations by S, and its ICT level by φ. Let s denote the establishment location and k the market location.

Let market k be given. The firm's sales from market k are:

$$\text{sales}_{oS\varphi k} = \frac{\sigma^{1-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma} z^{\sigma-1} E_k P_k^{\sigma-1} \left(\Phi_{oS\varphi k}\right)^{\frac{\sigma-1}{\theta}},$$

where $\tilde{\Gamma}$ is a constant, E_k and P_k are the consumer's expenditure on and the price index for manufacturing goods, $\Phi_{oS\varphi k}$ is the firm's production potential for market k, θ is the shape parameter of Fréchet distributions for establishment-specific productivity, and σ is the elasticity of substitution across varieties in consumer preference.

The sales share of the establishment at s equals its contribution to the firm's production potential to the market. That is, the sales from market k generated from the establishment at $s \in S$ are:

$$\begin{aligned}\text{sales}_{oS\varphi k \leftarrow s} &= \frac{(T_s/w_s)^{\theta} d_{os\varphi}^{-\theta} \tau_{sk}^{-\theta}}{\Phi_{oS\varphi k}} \times \text{sales}_{oS\varphi k} \\ &= \frac{\sigma^{1-\sigma}}{(\sigma-1)^{1-\sigma}}\tilde{\Gamma} z^{\sigma-1} E_k P_k^{\sigma-1} \Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}} (T_s/w_s)^{\theta} d_{os\varphi}^{-\theta} \tau_{sk}^{-\theta}. \end{aligned} \tag{34}$$

Here, T_s denotes the state of technology in location s, w_s the location's wage rate, τ_{sk} the shipping cost to market k, and $d_{os\varphi}$ the location-pair communication costs, which depend on the firm's ICT level.

Then, the share of the firm's total sales generated by the establishment at s is:

$$\zeta_{oS\varphi,s} = \frac{\sum_k \text{sales}_{oS\varphi k \leftarrow s}}{\sum_k \text{sales}_{oS\varphi k}} = \left(\frac{T_s}{w_s}\right)^{\theta} d_{os\varphi}^{-\theta} \sum_k \left[\frac{E_k P_k^{\sigma-1} \Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{oS\varphi k'}^{\frac{\sigma-1}{\theta}}} \tau_{sk}^{-\theta}\right]. \tag{35}$$

Similarly, the sales share accounted for by the firm's headquarters is:

$$\zeta_{oS\varphi,o} = \frac{\sum_k \text{sales}_{oS\varphi k \leftarrow o}}{\sum_k \text{sales}_{oS\varphi k}} = \left(\frac{T_o}{w_o}\right)^{\theta} d_{oo\varphi}^{-\theta} \sum_k \left[\frac{E_k P_k^{\sigma-1} \Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{oS\varphi k'}^{\frac{\sigma-1}{\theta}}} \tau_{ok}^{-\theta}\right]. \tag{36}$$

Combining Equations (35) and (35), we can derive the logarithm of the sales share at non-establishment locations $s \in S, s \neq o$, normalized by the logarithm of the headquarters sales share,

as:

$$\begin{aligned}\log \tilde{\zeta}_{oS\varphi,s} &\equiv \log \zeta_{oS\varphi,s} - \log \zeta_{oS\varphi,o} \\ &= -\theta \log d_{os\varphi} + \log\left(\sum_k \omega_{oS\varphi k}\, \tau_{sk}^{-\theta}\right) \\ &\underbrace{-\theta \log T_o + \theta \log w_o - \log\left(\sum_k \omega_{oS\varphi k}\, \tau_{ok}^{-\theta}\right)}_{\equiv \xi_{oS\varphi}} + \underbrace{\theta \log T_s - \theta \log w_s}_{\equiv \xi_s},\end{aligned}$$

where $\omega_{oS\varphi k} \equiv \frac{E_k P_k^{\sigma-1} \Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{oS\varphi k'}^{\frac{\sigma-\theta-1}{\theta}}}$. Here, I use the assumption that $d_{oo\varphi} = 1$. Additionally, I add and subtract a headquarters—set–ICT-specific term, i.e., $\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{oS\varphi k'}^{\frac{\sigma-\theta-1}{\theta}}$. Reorganize the equation above, and we can obtain that

$$\log \tilde{\zeta}_{oS\varphi,s} = -\theta \log d_{os\varphi} + \log\left(\sum_k \omega_{oS\varphi k}\, \tau_{sk}^{-\theta}\right) + \xi_{oS} + \xi_s. \tag{37}$$

11.4 ICT Adoption and the Within-Firm Sales Distribution

This appendix section shows how ICT adoption changes a firm's production at the intensive margin, particularly within-firm sales shares and thus labor allocation, across its establishments.

Consider a simple case where there are three locations {HQ,L,H}. HQ represents the firm's headquarters location. Suppose that the firm has two establishments, its headquarters in HQ and another in L. The share of total sales that is generated by the firm's establishment in location $s \in \{HQ, L\}$ is:

$$\zeta_{HQ,s}(\{HQ,L\},\varphi) = \sum_k \left[\underbrace{\frac{E_k P_k^{\sigma-1} \left(\Phi_{HQ,k}(\{HQ,L\},\varphi)\right)^{\frac{\sigma-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \left(\Phi_{HQ,k'}(\{HQ,L\},\varphi)\right)^{\frac{\sigma-1}{\theta}}}}_{\substack{\text{Share of sales from market } k \\ \equiv B_{HQ,k}(\{HQ,L\},\varphi)}} \underbrace{\frac{(T_s/w_s)^\theta d_{HQ,s}(\varphi)^{-\theta} \tau_{sk}^{-\theta}}{\Phi_{HQ,k}(\{HQ,L\},\varphi)}}_{\substack{\text{Share of sales from market } k \\ \text{generated at establishment } s \\ \equiv \zeta_{HQ,k\leftarrow s}(\{HQ,L\},\varphi)}} \right],$$

where $\Phi_{HQ,k}(\{HQ,L\},\varphi) \equiv \sum_{s' \in \{HQ,L\}} (T_{s'}/w_{s'})^\theta d_{HQ,s'}(\varphi)^{-\theta} \tau_{s'k}^{-\theta}$ represents the production potential of the firm to market k. The first term captures the share of total sales from market k, and the second term captures the share of sales from market k that is accounted for by the establishment in location $s \in \{HQ, L\}$. Assume that trade costs are symmetric and satisfy the triangle inequality, and normalize the trade costs to one when the market is the same as the establishment location.[60]

Holding the firm's set of locations unchanged and equilibrium prices constant, I show that

[60] That is, $\tau_{sk} = \tau_{ks}$, $\tau_{sk} < \tau_{sk'} \times \tau_{k'k}$, where $s, k, k' \in \{HQ, L, H\}$, and $\tau_{sk} = 1, s = k$.

adopting better ICT increases the share of total sales by the establishment in L; that is,

$$\zeta_{HQ,L}(\{H,L\},\overline{\varphi}) > \zeta_{HQ,L}(\{H,L\},\underline{\varphi}).$$

Derivation: Denote the share of the firm's total sales from market k by $B_{HQ,k}(\{HQ,L\},\varphi)$ and, within the sales from market k, the share accounted for by the establishment at location $s \in \{HQ,L\}$ by $\zeta_{HQ,k\leftarrow s}(\{HQ,L\},\varphi)$. We can write the sales share of the establishment in L as:

$$\zeta_{HQ,L}(\{H,L\},\varphi) = \sum_{k=HQ,L,H} B_{HQ,k}(\{HQ,L\},\varphi) \times \zeta_{HQ,k\leftarrow L}(\{HQ,L\},\varphi)$$

For simplicity, I write the establishment location set $\{HQ,L\}$ as $(\cdot)$. The difference in the sales share of the establishment in L when it has high and low ICT levels is:

$$\begin{aligned}
\zeta_{HQ,L}(\cdot,\overline{\varphi}) - \zeta_{HQ,L}(\cdot,\underline{\varphi}) &= \sum_{k=HQ,L,H} \Big[B_{HQ,k}(\cdot,\overline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi}) \Big] \\
&= \sum_{k=HQ,L,H} \Big[B_{HQ,k}(\cdot,\overline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) \\
&\qquad + B_{HQ,k}(\cdot,\underline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi}) \times \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi}) \Big] \\
&= \sum_{k=HQ,L,H} \Big[B_{HQ,k}(\cdot,\underline{\varphi}) \times \underbrace{\Big(\zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi})\Big)}_{\substack{\text{Change in the share of sales from market } k \\ \text{generated at establishment } L}} \Big] \\
&+ \sum_{k=HQ,L,H} \Big[\underbrace{\Big(B_{HQ,k}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi})\Big)}_{\text{Change in the share of sales from market } k} \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) \Big] \qquad (38)
\end{aligned}$$

I first show that for any market k, adopting better ICT increases the share of sales from that market that is generated at establishment L, which reflects improvements in production technology at establishment L. That is, the first summation term is positive.

Let market $k \in \{HQ,L,H\}$ be given. Then, we can obtain that

$$\begin{aligned}
\zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) &= \frac{(T_L/w_L)^\theta d_{HQ,L}(\overline{\varphi})^{-\theta} \tau_{L,k}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,k}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\overline{\varphi})^{-\theta} \tau_{L,k}^{-\theta}} \\
&= \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,k}}{\tau_{L,k}}\right)^{-\theta} d_{HQ,L}(\overline{\varphi})^\theta + 1} \\
&> \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,k}}{\tau_{L,k}}\right)^{-\theta} d_{HQ,L}(\underline{\varphi})^\theta + 1} \equiv \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi}),
\end{aligned}$$

where we use the assumptions that $d_{HQ,HQ}(\overline{\varphi}) = d_{HQ,HQ}(\underline{\varphi}) = 1$ for the first equality and that $d_{HQ,L}(\overline{\varphi}) < d_{HQ,L}(\underline{\varphi})$ for the inequality. Thus, $\zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,k\leftarrow L}(\cdot,\underline{\varphi}) > 0$ for any market $k \in \{HQ,L,H\}$. Therefore, the first summation term is positive.

Now, before showing that the second summation is positive, I show a few properties.

Claim: The sales share of the establishment in L to each market, i.e., $\zeta_{HQ,k\leftarrow L}(\cdot,\varphi)$, satisfies the following relationship.

$$\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,H\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,L\leftarrow L}(\cdot,\varphi), \text{ where } \varphi = \underline{\varphi}, \overline{\varphi}. \tag{39}$$

Derivation: Let the ICT level $\varphi \in \{\underline{\varphi}, \overline{\varphi}\}$ be given. By definition, we have that

$$\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) = \frac{(T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,HQ}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,HQ}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,HQ}^{-\theta}} = \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,HQ}}{\tau_{L,HQ}}\right)^{-\theta} d_{HQ,L}(\varphi)^\theta + 1}$$

$$\zeta_{HQ,L\leftarrow L}(\cdot,\varphi) = \frac{(T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,L}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,L}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,L}^{-\theta}} = \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,L}}{\tau_{L,L}}\right)^{-\theta} d_{HQ,L}(\varphi)^\theta + 1}$$

$$\zeta_{HQ,H\leftarrow L}(\cdot,\varphi) = \frac{(T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,H}^{-\theta}}{(T_{HQ}/w_{HQ})^\theta \tau_{HQ,H}^{-\theta} + (T_L/w_L)^\theta d_{HQ,L}(\varphi)^{-\theta}\tau_{L,H}^{-\theta}} = \frac{1}{\left(\frac{T_{HQ}/w_{HQ}}{T_L/w_L}\right)^\theta \left(\frac{\tau_{HQ,H}}{\tau_{L,H}}\right)^{-\theta} d_{HQ,L}(\varphi)^\theta + 1}$$

Since $\tau_{HQ,H} < \tau_{HQ,L}\tau_{L,H}$ by the triangle inequality of trade costs and $\tau_{L,L} = 1$ by normalization, we have that $\frac{\tau_{HQ,L}}{\tau_{L,L}} > \frac{\tau_{HQ,H}}{\tau_{L,H}}$. Thus, we can obtain that $\zeta_{HQ,L\leftarrow L}(\cdot,\varphi) > \zeta_{HQ,H\leftarrow L}(\cdot,\varphi)$. Similarly, since $\tau_{L,H} < \tau_{L,HQ}\tau_{HQ,H}$ and $\tau_{HQ,HQ} = 1$, we can obtain that $\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,H\leftarrow L}(\cdot,\varphi)$.

Therefore, we have that $\zeta_{HQ,HQ\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,H\leftarrow L}(\cdot,\varphi) < \zeta_{HQ,L\leftarrow L}(\cdot,\varphi)$ for $\varphi = \underline{\varphi}, \overline{\varphi}$.

Claim: Adopting better ICT increases the firm's production potential corresponding to market L relative to its production potential corresponding to markets HQ and H. That is,

$$\frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})}{\Phi_{HQ,k}(\cdot,\overline{\varphi})} > \frac{\Phi_{HQ,L}(\cdot,\underline{\varphi})}{\Phi_{HQ,k}(\cdot,\underline{\varphi})}, \text{ where } k = HQ, H. \tag{40}$$

In addition, adopting better ICT increases the firm's production potential to market H relative to its production potential to market HQ. That is,

$$\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})} > \frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}. \tag{41}$$

Derivation: Note that $\Phi_{HQ,k}(\cdot,\overline{\varphi}) - \Phi_{HQ,k}(\cdot,\underline{\varphi}) = (T_L/w_L)^\theta [d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta}]\tau_{L,k}^{-\theta}, k \in \{HQ, L, H\}$. Thus, improvements to the production potential corresponding to market k increase in the trade cost from establishment L to market k.

Let market $k \in \{HQ, H\}$ be given. We can show that

$$
\begin{aligned}
&\frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})}{\Phi_{HQ,k}(\cdot,\overline{\varphi})} - \frac{\Phi_{HQ,L}(\cdot,\underline{\varphi})}{\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi}) - \Phi_{HQ,L}(\cdot,\underline{\varphi})\Phi_{HQ,k}(\cdot,\overline{\varphi})}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \frac{[\Phi_{HQ,L}(\cdot,\overline{\varphi}) - \Phi_{HQ,L}(\cdot,\underline{\varphi})]\Phi_{HQ,k}(\cdot,\underline{\varphi}) - \Phi_{HQ,L}(\cdot,\underline{\varphi})[\Phi_{HQ,k}(\cdot,\overline{\varphi}) - \Phi_{HQ,k}(\cdot,\underline{\varphi})]}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \Bigg\{ \Big(\frac{T_L}{w_L}\Big)^{\theta} \Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta} \Big] \tau_{L,L}^{-\theta} \Big[\Big(\frac{T_{HQ}}{w_{HQ}}\Big)^{\theta} \tau_{HQ,k}^{-\theta} + \Big(\frac{T_L}{w_L}\Big)^{\theta} d_{HQ,L}(\underline{\varphi})^{-\theta} \tau_{L,k}^{-\theta} \Big] \\
&\quad\quad - \Big[\Big(\frac{T_{HQ}}{w_{HQ}}\Big)^{\theta} \tau_{HQ,L}^{-\theta} + \Big(\frac{T_L}{w_L}\Big)^{\theta} d_{HQ,L}(\underline{\varphi})^{-\theta} \tau_{L,L}^{-\theta} \Big] \Big(\frac{T_L}{w_L}\Big)^{\theta} \Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta} \Big] \tau_{L,k}^{-\theta} \Bigg\} \\
&\quad\quad \times \frac{1}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} \\
&\quad= \frac{\Big(\frac{T_L}{w_L}\Big)^{\theta} \Big(\frac{T_{HQ}}{w_{HQ}}\Big)^{\theta} \Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta} \Big] \big(\tau_{HQ,k}^{-\theta} - \tau_{HQ,L}^{-\theta} \tau_{L,k}^{-\theta} \big)}{\Phi_{HQ,k}(\cdot,\overline{\varphi})\Phi_{HQ,k}(\cdot,\underline{\varphi})} > 0.
\end{aligned}
$$

The last inequality follows from the facts that $d_{HQ,L}(\overline{\varphi}) < d_{HQ,L}(\underline{\varphi})$ and that the trade costs satisfy the triangle inequality. Similarly, we can show that

$$
\begin{aligned}
&\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})} - \frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})} \\
&\quad= \frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})\Phi_{HQ,HQ}(\cdot,\underline{\varphi}) - \Phi_{HQ,H}(\cdot,\underline{\varphi})\Phi_{HQ,HQ}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\Phi_{HQ,HQ}(\cdot,\underline{\varphi})} \\
&\quad= \frac{[\Phi_{HQ,H}(\cdot,\overline{\varphi}) - \Phi_{HQ,H}(\cdot,\underline{\varphi})]\Phi_{HQ,HQ}(\cdot,\underline{\varphi}) - \Phi_{HQ,H}(\cdot,\underline{\varphi})[\Phi_{HQ,HQ}(\cdot,\overline{\varphi}) - \Phi_{HQ,HQ}(\cdot,\underline{\varphi})]}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\Phi_{HQ,HQ}(\cdot,\underline{\varphi})} \\
&\quad= \Bigg\{ \Big(\frac{T_L}{w_L}\Big)^{\theta} \Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta} \Big] \tau_{L,H}^{-\theta} \Big[\Big(\frac{T_{HQ}}{w_{HQ}}\Big)^{\theta} \tau_{HQ,HQ}^{-\theta} + \Big(\frac{T_L}{w_L}\Big)^{\theta} d_{HQ,L}(\underline{\varphi})^{-\theta} \tau_{L,HQ}^{-\theta} \Big] \\
&\quad\quad - \Big[\Big(\frac{T_{HQ}}{w_{HQ}}\Big)^{\theta} \tau_{HQ,H}^{-\theta} + \Big(\frac{T_L}{w_L}\Big)^{\theta} d_{HQ,L}(\underline{\varphi})^{-\theta} \tau_{L,H}^{-\theta} \Big] \Big(\frac{T_L}{w_L}\Big)^{\theta} \Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta} \Big] \tau_{L,HQ}^{-\theta} \Bigg\} \\
&\quad\quad \times \frac{1}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\Phi_{HQ,HQ}(\cdot,\underline{\varphi})} \\
&\quad= \frac{\Big(\frac{T_L}{w_L}\Big)^{\theta} \Big(\frac{T_{HQ}}{w_{HQ}}\Big)^{\theta} \Big[d_{HQ,L}(\overline{\varphi})^{-\theta} - d_{HQ,L}(\underline{\varphi})^{-\theta} \Big] \big(\tau_{L,H}^{-\theta} - \tau_{L,HQ}^{-\theta} \tau_{HQ,H}^{-\theta} \big)}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\Phi_{HQ,HQ}(\cdot,\underline{\varphi})} > 0.
\end{aligned}
$$

Claim: Adopting better ICT increases the share of sales from market L but decreases the share of

sales from market HQ. That is,

$$B_{HQ,L}(\cdot,\overline{\varphi}) > B_{HQ,L}(\cdot,\underline{\varphi}), \tag{42}$$

$$B_{HQ,HQ}(\cdot,\overline{\varphi}) < B_{HQ,HQ}(\cdot,\underline{\varphi}). \tag{43}$$

Derivation: Denote $D_k = E_k P_k^{\sigma-1}, k = HQ, L, H$. By definition, we have that

$$\begin{aligned}
B_{HQ,L}(\cdot,\overline{\varphi}) &= \frac{D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{\sum_{k=HQ,L,H} D_k\big(\Phi_{HQ,k}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_H\big(\Phi_{HQ,H}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{1}{\frac{D_{HQ}}{D_L}\left(\frac{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})}{\Phi_{HQ,L}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + 1 + \frac{D_H}{D_L}\left(\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,L}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \\
&> \frac{1}{\frac{D_{HQ}}{D_L}\left(\frac{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}{\Phi_{HQ,L}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + 1 + \frac{D_H}{D_L}\left(\frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,L}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \equiv B_{HQ,L}(\cdot,\underline{\varphi}),
\end{aligned}$$

where the inequality follows from inequality (40). Similarly, we can write the sales share from market HQ with high ICT as

$$\begin{aligned}
B_{HQ,HQ}(\cdot,\overline{\varphi}) &= \frac{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{\sum_{k=HQ,L,H} D_k\big(\Phi_{HQ,k}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}}{D_{HQ}\big(\Phi_{HQ,HQ}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_L\big(\Phi_{HQ,L}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}} + D_H\big(\Phi_{HQ,H}(\cdot,\overline{\varphi})\big)^{\frac{\sigma-1}{\theta}}} \\
&= \frac{1}{1 + \frac{D_L}{D_{HQ}}\left(\frac{\Phi_{HQ,L}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + \frac{D_H}{D_{HQ}}\left(\frac{\Phi_{HQ,H}(\cdot,\overline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\overline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \\
&< \frac{1}{1 + \frac{D_L}{D_{HQ}}\left(\frac{\Phi_{HQ,L}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}} + \frac{D_H}{D_{HQ}}\left(\frac{\Phi_{HQ,H}(\cdot,\underline{\varphi})}{\Phi_{HQ,HQ}(\cdot,\underline{\varphi})}\right)^{\frac{\sigma-1}{\theta}}} \equiv B_{HQ,HQ}(\cdot,\underline{\varphi})
\end{aligned}$$

where the inequality follows from inequalities (40) and (41).

Finally, we can show that the second summation in Equation (38) is positive. Denote the change in the sales share from market k by $\Delta B_{HQ,k}(\cdot) \equiv B_{HQ,k}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi})$, $k \in \{HQ, L, H\}$. Since the total sales shares sum up to 1, i.e., $\sum_{k=HQ,L,H} B_{HQ,k}(\cdot,\varphi) = 1$, we have that $\Delta B_{HQ,H}(\cdot) =$

$-\Delta B_{HQ,HQ}(\cdot) - \Delta B_{HQ,L}(\cdot)$. Then, we can write the second term in Equation (38) as:

$$
\begin{aligned}
&\sum_{k=HQ,L,H} \Big[\Big(B_{HQ,k}(\cdot,\overline{\varphi}) - B_{HQ,k}(\cdot,\underline{\varphi})\Big) \times \zeta_{HQ,k\leftarrow L}(\cdot,\overline{\varphi})\Big] \\
&= \Delta B_{HQ,HQ}(\cdot) \times \zeta_{HQ,HQ\leftarrow L}(\cdot,\overline{\varphi}) + \Delta B_{HQ,L}(\cdot) \times \zeta_{HQ,L\leftarrow L}(\cdot,\overline{\varphi}) + \Delta B_{HQ,H}(\cdot) \times \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi}) \\
&= \underbrace{\Delta B_{HQ,HQ}(\cdot)}_{<0}\underbrace{[\zeta_{HQ,HQ\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi})]}_{<0} + \underbrace{\Delta B_{HQ,L}(\cdot)}_{>0}\underbrace{[\zeta_{HQ,L\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi})]}_{>0} > 0
\end{aligned}
$$

By inequalities (43) and (42), we have that $\Delta B_{HQ,HQ}(\cdot) < 0$ and $\Delta B_{HQ,L}(\cdot) > 0$. By the relationship of the sales share of the establishment in L to each market in (39), we have that $\zeta_{HQ,HQ\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi}) < 0$ and $\zeta_{HQ,L\leftarrow L}(\cdot,\overline{\varphi}) - \zeta_{HQ,H\leftarrow L}(\cdot,\overline{\varphi}) > 0$. Thus, the summation term is positive.

Hence, we have that adopting better ICT increases the sales share of the establishment in L. Thanks to CES demand and monopolistic competition, wage payments are proportional to sales. With wage rates held constant, employment is proportional to sales. Therefore, adopting better ICT increases the employment share at the establishment in L.

11.5 Decomposition of Local Efficiency

In this appendix section, I decompose local efficiency, reflected in the local price index, into the contributions from different types of firms. Let location s be given. Denote the local price index by P_s, which can be written as follows.

$$
\begin{aligned}
P_s = \frac{\sigma}{\sigma-1}\tilde{\Gamma}^{\frac{1}{1-\sigma}} \Bigg\{ & \int_Z \mathbb{1}[\{s\} = S_s(\varphi(z),z)]\Big(\frac{h(\varphi(z))}{z}\Big) \underbrace{(T_s/w_s)^{-(1-\sigma)}}_{\text{Channel 1}} d\mu_s(z) \\
& + \int_Z \underbrace{\mathbb{1}[\{s\} \subset S_s(\varphi(z),z)]}_{\text{Channel 4}} \Big(\frac{h(\varphi(z))}{z}\Big) \Big[\underbrace{(T_s/w_s)^{\theta}}_{\text{Channel 1}} + \underbrace{\sum_{\substack{s'\in S_s(\varphi(z),z)\\ s'\neq s}} (T_{s'}/w_{s'})^{\theta}(d_{ss'}(\varphi(z))\tau_{s's})^{-\theta}}_{\text{Channel 4}} \Big]^{-\frac{1-\sigma}{\theta}} d\mu_s(z) \\
& + \sum_{o\neq s} \int_Z \underbrace{\mathbb{1}[s \in S_o(\varphi(z),z)]}_{\text{Channel 3(b)}} \Big(\frac{h(\varphi(z))}{z}\Big) \Big[\underbrace{(T_o/w_o)^{\theta}\tau_{os}^{-\theta}}_{\text{Channel 2}} + \underbrace{(T_s/w_s)^{\theta}(d_{os}(\varphi(z)))^{-\theta}}_{\text{Channel 3(a)}} + \\
& \qquad \underbrace{\sum_{\substack{s'\in S_o(\varphi(z),z)\\ s'\neq s, s'\neq o}} (T_{s'}/w_{s'})^{\theta}(d_{os'}(\varphi(z))\tau_{s's})^{-\theta}}_{\text{Channel 4}} \Big]^{-\frac{1-\sigma}{\theta}} d\mu_o(z) \\
& + \sum_{o\neq s} \int_Z \mathbb{1}[s \notin S_o(\varphi(z),z)]\Big(\frac{h(\varphi(z))}{z}\Big) \Big[\underbrace{(T_o/w_o)^{\theta}\tau_{os}^{-\theta}}_{\text{Channel 2}} + \underbrace{\sum_{\substack{s'\in S_o(\varphi(z),z)\\ s'\neq s, s'\neq o}} (T_{s'}/w_{s'})^{\theta}(d_{os'}(\varphi(z))\tau_{s's})^{-\theta}}_{\text{Channel 4}} \Big]^{-\frac{1-\sigma}{\theta}} d\mu_o(z) \Bigg\}^{\frac{1}{1-\sigma}}
\end{aligned}
\tag{44}
$$

The first line summarizes the prices charged by local firms that operate only in location s, i.e., local single-unit firms. Following an ICT cost reduction, these firms contribute to local

efficiency improvement by increasing effective productivity $z/h(\varphi(z))$ (channel 1). The second line shows that in addition to the local production channel (channel 1), local multi-unit firms can reduce their costs of communication with their nonheadquarters establishments, expand to more locations, and enhance local efficiency through third-location trade (channel 4). The third and fourth lines summarize the prices charged by outside firms with establishments in location s. Their headquarters' production affects local efficiency in s through the traditional trade channel (channel 2). Moreover, their local establishments benefit from productivity improvements and the reduction in the cost of communicating with headquarters, which directly raises local efficiency in location s (channel 3(a)). As firms reorganize their geographic coverage, these firms also affect local efficiency through entry and exit (channel 3(b)). Additionally, nonheadquarters establishments of outside firms affect local efficiency through third-location trade (channel 4). The last line shows that outside firms that do not have a local establishment still affect local efficiency through the traditional and third-location trade channels.

12 Estimation Appendix

12.1 First-Stage Regression with Employment Share

Since the production function is Cobb–Douglas with labor as the only input and firms compete monopolistically, the establishment's wages are proportional to its sales with a factor of $(\sigma - 1)/\sigma$. Combining this with the establishment sales in Equation (34), we can obtain the wages at establishment $s \in S$ as:

$$w_s L_{oS\varphi,s} = \frac{\sigma-1}{\sigma}\sum_k \text{sales}_{oS\varphi k\leftarrow s} = \frac{(\sigma-1)^\sigma}{\sigma^\sigma}\tilde{\Gamma} z^{\sigma-1}\left(\frac{T_s}{w_s}\right)^\theta d_{os\varphi}^{-\theta}\sum_k (E_k P_k^{\sigma-1}\Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}\tau_{sk}^{-\theta}). \quad (45)$$

Then, the employment at establishment $s \in S$ is:

$$L_{oS\varphi,s} = \frac{(\sigma-1)^\sigma}{\sigma^\sigma}\tilde{\Gamma} z^{\sigma-1} T_s^\theta w_s^{-(\theta+1)} d_{os\varphi}^{-\theta}\sum_k (E_k P_k^{\sigma-1}\Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}\tau_{sk}^{-\theta}). \quad (46)$$

Similarly, the employment at the headquarters o is:

$$L_{oS\varphi,o} = \frac{(\sigma-1)^\sigma}{\sigma^\sigma}\tilde{\Gamma} z^{\sigma-1} T_o^\theta w_o^{-(\theta+1)}\sum_k (E_k P_k^{\sigma-1}\Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}\tau_{sk}^{-\theta}), \quad (47)$$

where we take into account that the location-pair communication cost is zero at the headquarters.

Therefore, we can derive the logarithm of the employment share at nonestablishment locations

$s \in S, s \neq o$, normalized by the logarithm of the headquarters employment share, as:

$$\begin{aligned}\log \tilde{\zeta}_{oS\varphi,s} &\equiv \log \zeta_{oS\varphi,s} - \log \zeta_{oS\varphi,o} = \log L_{oS\varphi,s} - \log L_{oS\varphi,o} \\ &= -\theta \log d_{os\varphi} + \log\left(\sum_k \omega_{oS\varphi k}\, \tau_{sk}^{-\theta}\right) \\ &\underbrace{-\theta \log T_o + (\theta+1)\log w_o - \log\left(\sum_k \omega_{oS\varphi k}\, \tau_{ok}^{-\theta}\right)}_{\equiv \xi_{oS\varphi}} + \underbrace{\theta \log T_s - (\theta+1)\log w_s}_{\equiv \xi_s},\end{aligned}$$

where $\omega_{oS\varphi k} \equiv \frac{E_k P_k^{\sigma-1} \Phi_{oS\varphi k}^{\frac{\sigma-\theta-1}{\theta}}}{\sum_{k'} E_{k'} P_{k'}^{\sigma-1} \Phi_{oS\varphi k'}^{\frac{\sigma-\theta-1}{\theta}}}$. That is,

$$\log \tilde{\zeta}_{oS\varphi,s} = -\theta \log d_{os\varphi} + \log\left(\sum_k \omega_{oS\varphi k}\, \tau_{sk}^{-\theta}\right) + \xi_{oS} + \xi_s, \tag{48}$$

which is of the same form as the normalized sales share.

13 Policy Simulation Appendix

13.1 Decomposition of the Price Index

Denote the firm by i and the firm headquarters location by o. In each market k, the ideal price index is defined by $P_k = \left(\sum_{o=1}^{N} \int_0^{m_o} p_{ok}(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}$, where m_o is the exogenous mass of firms headquartered in location o and $p_{ok}(i)$ is the firm-specific price charged in market k by the firm. Depending on whether a firm is headquartered in location k (i.e., local firms versus outside firms) and whether a firm sets up an establishment in location k in the benchmark or counterfactual equilibrium, we can decompose the price index into the contributions from five types of firms:

$$P_k^{1-\sigma} = (P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (P_k^{\text{out},00})^{1-\sigma},$$

where P_k^{local} is the price index of local firms, $P_k^{\text{out},11}$ is the price index of outside firms that set up establishments in location k in both the benchmark and counterfactual equilibria, $P_k^{\text{out},10}$ is the price index of outside firms that set up establishments in the location in the benchmark equilibrium but exit in the counterfactual equilibrium, $P_k^{\text{out},01}$ is the price index of outside firms that do not set up establishments in the location in the benchmark equilibrium but enter the location in the counterfactual equilibrium, and $P_k^{\text{out},00}$ is the price index of outside firms that do not set up establishments in the location in either the benchmark or the counterfactual equilibrium. Specifically, these price indices are defined as follows. Let $S^0(i)$ and $S^1(i)$ be the set of establishment locations

of firm i in the benchmark equilibrium and counterfactual equilibrium, respectively. Then, we can express the price index of each type of firm by:

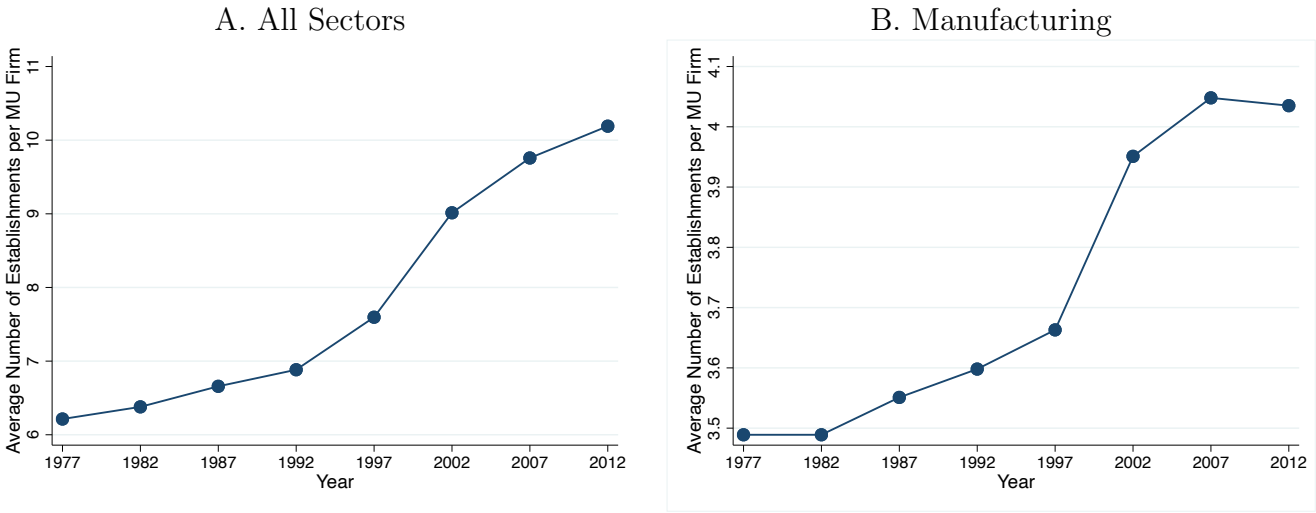
$$
\begin{aligned}
P_k^{\text{local}} &= \left(\int_0^{m_k} p_{kk}(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},11} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \in S^0(i), k \in S^1(i)] \, p_{ok}(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},10} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \in S^0(i), k \notin S^1(i)] \, p_{ok}(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},01} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \notin S^0(i), k \in S^1(i)] \, p_{ok}(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} \\
P_k^{\text{out},00} &= \left(\sum_{o \neq k} \int_0^{m_o} \mathbb{1}[k \notin S^0(i), k \notin S^1(i)] \, p_{ok}(i)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}} .
\end{aligned}
$$

Let P_k denote the price index in location k in the benchmark equilibrium and $\tilde{P}_k$ the price index in the counterfactual equilibrium. As efficiency gains are captured by changes in the inverse of the price index, we can thus decompose the changes in efficiency as follows:

$$
\begin{aligned}
&\log \tilde{W}_k - \log W_k = \log 1/\tilde{P}_k - \log 1/P_k = \log P_k - \log \tilde{P}_k \\
&= \frac{1}{1-\sigma}\Bigg[\log\left((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (P_k^{\text{out},00})^{1-\sigma}\right) - \\
&\qquad \log\left((\tilde{P}_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right)\Bigg] \\
&= \frac{1}{1-\sigma}\Bigg[\log\left((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (P_k^{\text{out},00})^{1-\sigma}\right) - \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (P_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) + \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) - \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (P_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) + \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) - \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (P_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) + \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) - \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) + \\
&\qquad \log\left((P_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right) - \\
&\qquad \log\left((\tilde{P}_k^{\text{local}})^{1-\sigma} + (\tilde{P}_k^{\text{out},11})^{1-\sigma} + (\tilde{P}_k^{\text{out},10})^{1-\sigma} + (\tilde{P}_k^{\text{out},01})^{1-\sigma} + (\tilde{P}_k^{\text{out},00})^{1-\sigma}\right)\Bigg] \\
&\equiv \left(\Delta^{\text{out},00} + \Delta^{\text{out},01} + \Delta^{\text{out},10} + \Delta^{\text{out},11} + \Delta^{\text{local}}\right),
\end{aligned}
$$

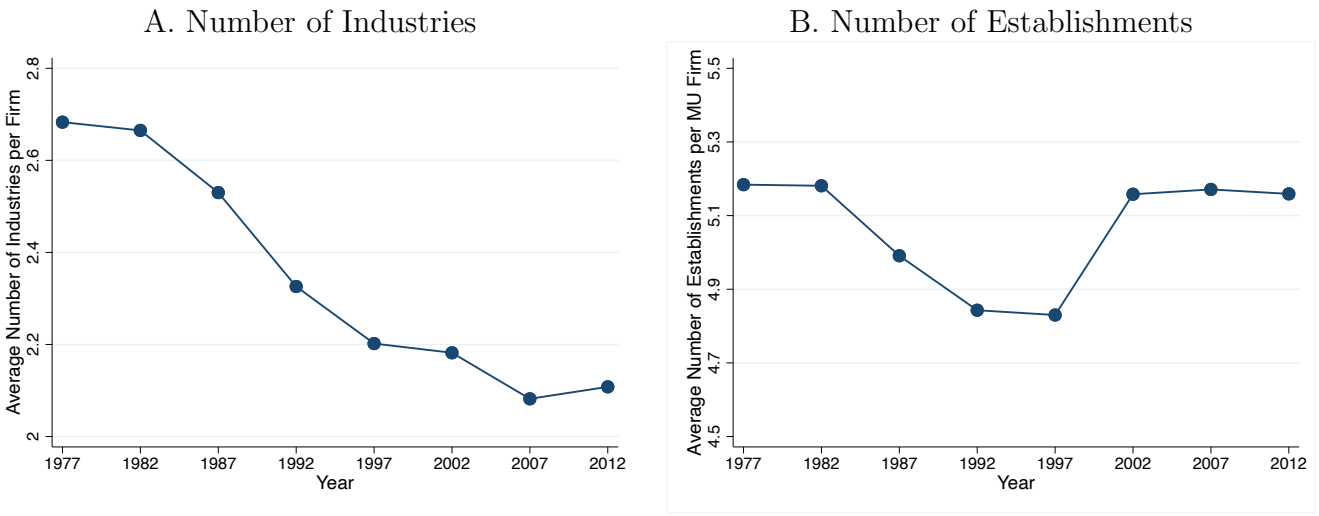
where Δ^{local}, $\Delta^{\text{out},11}$, $\Delta^{\text{out},10}$, $\Delta^{\text{out},01}$, and $\Delta^{\text{out},00}$ represent the contributions to the changes in the price index from the different types of firms.

Figure 10: **Number of Establishments per Firm for Multi-Unit Firms from 1977 to 2012**



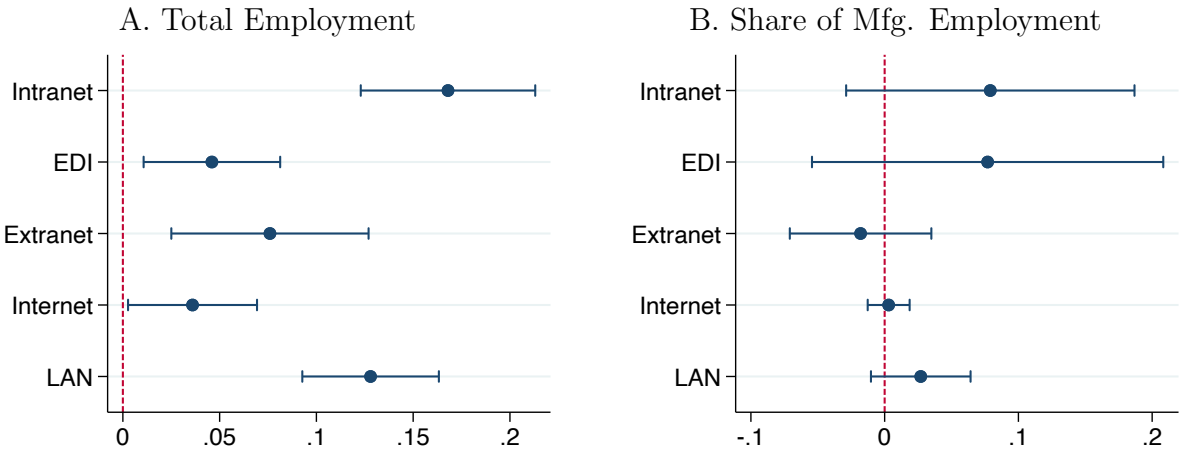
Notes: These figures plot the average number of establishments of multi-unit firms in the Longitudinal Business Database from 1977 to 2012. Panel A considers firms in all sectors, including utilities (22), construction (23), manufacturing (31–33), wholesale trade (42), retail trade (44–45), transportation and warehousing (48-49), information (51), finance and insurance (52), real estate and rental and leasing (53), professional, scientific, and technical services (54), management of companies and enterprises (55), administrative and support and waste management and remediation services (56), educational services (61), health care and social assistance (62), arts, entertainment, and recreation (63), accommodation and food services (72), and other services, except public administration (81). Panel A focuses on firms and their establishments in the manufacturing sector. Each firm is a FIRMID×6-digit NAICS industry pair. Multi-unit firms are firms with more than one establishment.

Figure 11: **Span of Control for Multi-Unit Firms, Alternative Firm Definition**



Notes: These figures show the span of control for multi-unit firms in the manufacturing sector from the Longitudinal Business Database (LBD). The firm is defined by the FIRMID. Multi-unit firms are firms with more than one establishment. Panel A plots the average number of industries of multi-unit firms. The industry is defined at the 6-digit NAICS level. Panel B plots the average number of establishments of multi-unit firms, including their establishments in multiple locations and multiple industries.

Figure 12: **ICT Adoption and Expansion**

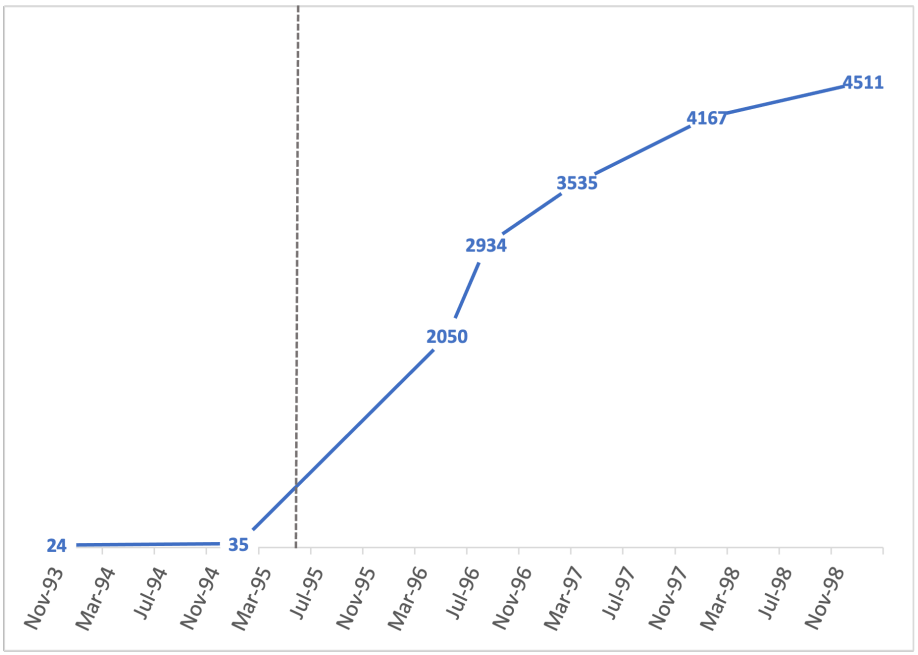


Notes: These figures use the matched sample of the Longitudinal Business Database (LBD) and the Computer Network Use Supplement (CNUS) and plot the coefficients of a regression of the form:

$$\Delta Y_{i,97-02} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,97}\gamma + \varepsilon_{i,97-02},$$

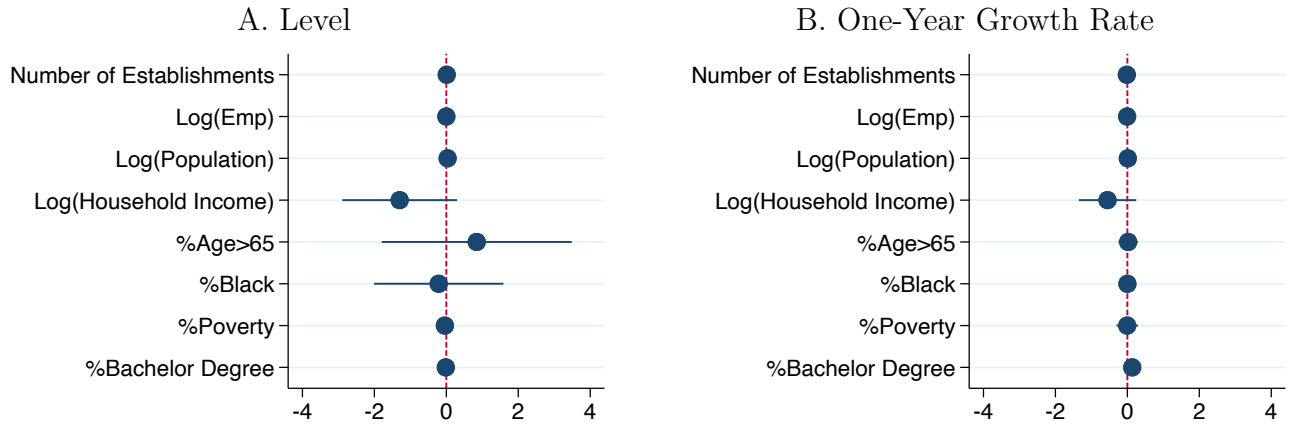
where the dependent variables $\Delta Y_{i,97-02}$ $(= \log Y_{i,02} - \log Y_{i,97})$ are the growth rate from 1997 to 2002 of firm i in total employment in all sectors (Panel C) and the share of manufacturing employment (Panel D). The independent variables include indicators set to one if firm i adopted Intranet, Electronic data interchange (EDI), Extranet, Internet, and Local area network (LAN) by 1999. $X_{i,97}$ is a vector of the firm's initial characteristics in 1997, including the logarithm of employment, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS Level. Confidence intervals are at the 95% level.

Figure 13: Number of Internet Service Providers (ISPs) Listed in *Boardwatch Magazine*



Notes: This figure plots the number of Internet service providers that were listed in *Boardwatch Magazine* from November 1993 to January 1999. These numbers are documented in Table 5.1 in Greenstein (2015).

Figure 14: **Regression Estimates of Distance to the Nearest NSFNET Node on Firm and County Characteristics**



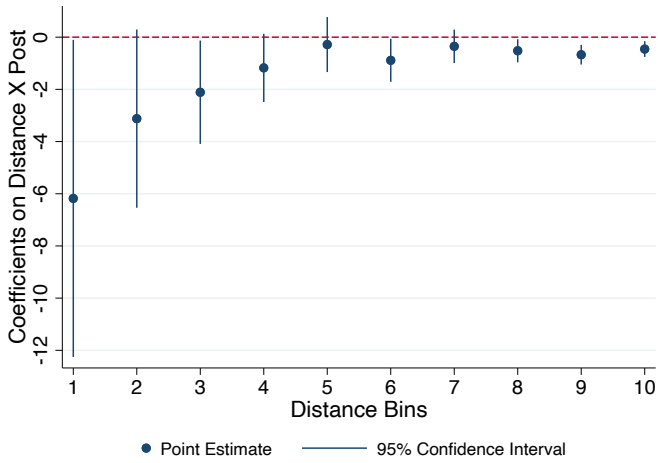
Notes: These figures plot the estimated coefficients of the following regression using observations from 1987:

$$\text{HQDistToNode}_i = \alpha + X_i\beta + \alpha_i^{\text{Industry}} + \alpha_i^{\text{State}} + u_i,$$

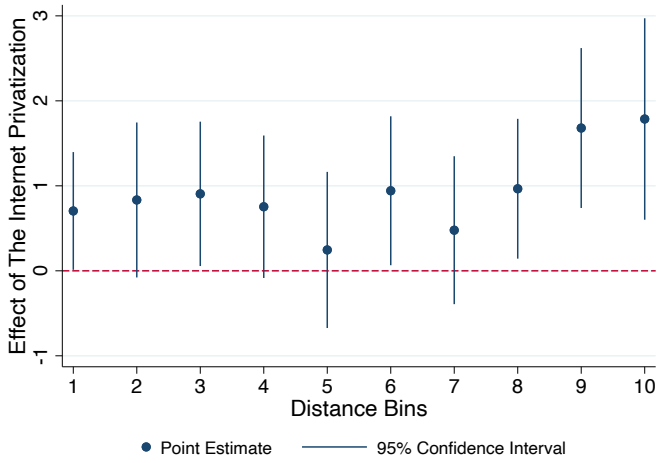
where the dependent variable is the distance from a firm's headquarters to the nearest NSFNET node, X_i includes the firm's number of establishments, logarithm of employment, county characteristics including the logarithm of local population, logarithm of median household income, share of the population below the poverty line, share of population over sixty-five years old, share of the black population, and share of the population with a bachelor's degree and above, as well as one-year growth rates in these covariates. $\alpha_i^{\text{Industry}}$ is the 4-digit NAICS industry fixed effect, and α_i^{State} is the state fixed effect. Standard errors are clustered at the county level. Panels A and B plot the estimated coefficients on the level and one-year growth rate of the firm and county covariates, respectively.

Figure 15: **Estimates of the Effect of ICT on Firms' Geographic Expansion: Distance Bins**

A. Estimated Coefficient for Each Distance Bin



B. Estimated Effect for Each Distance Bin

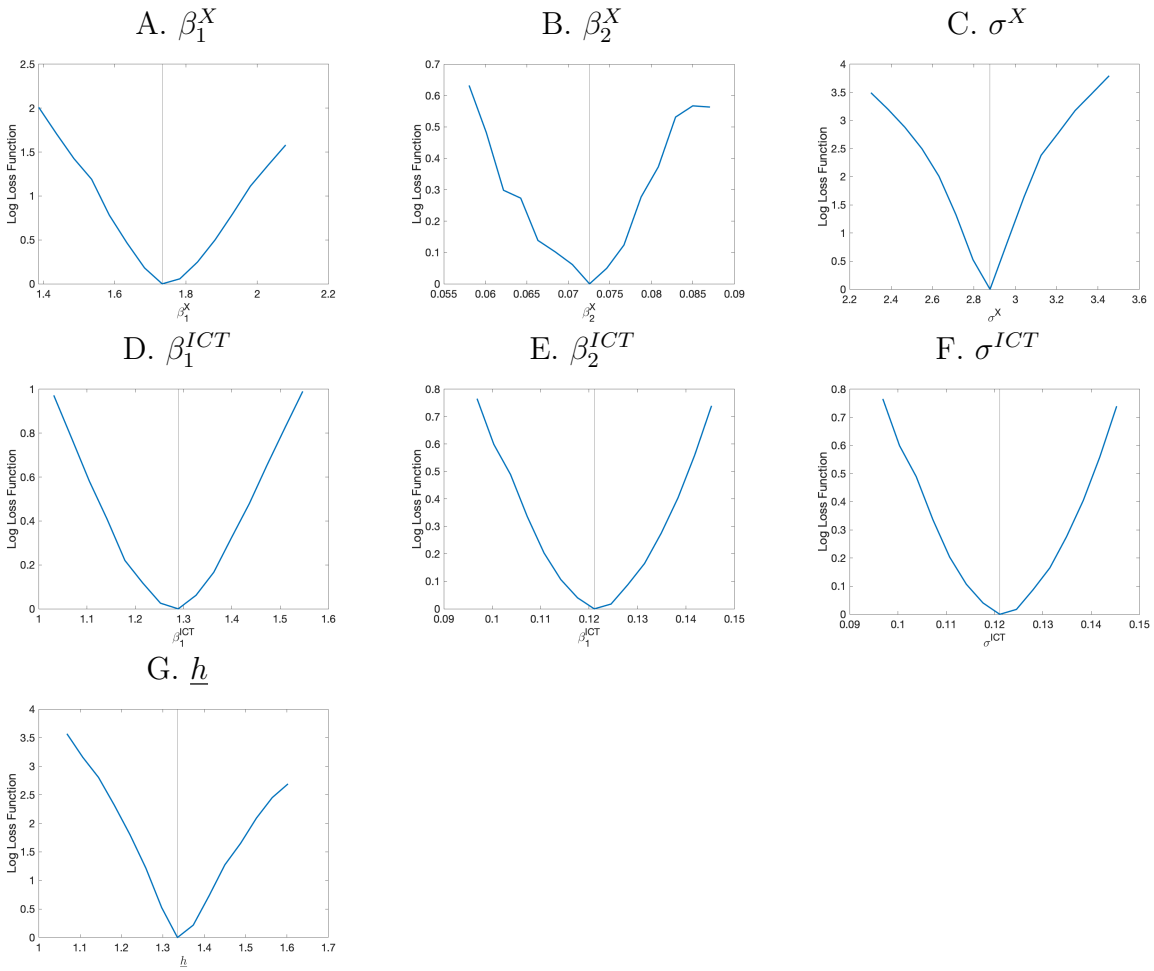


Notes: These figures show the effects of the Internet privatization on firms' geographic span of control for firms headquartered at different distances to the nearest NSFNET node by estimating the regression:

$$Y_{it,k} = \alpha_i + \sum_{k=1}^{10} \beta_k \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it,k},$$

where the dependent variable $Y_{it,k}$ is the number of establishments of firm i in year t and k indicates the kth decile of the distance distribution that the firm belongs to. α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, the shares of the black population and people over 65 years old, and the share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. Panel A plots the difference-in-differences coefficients on the interaction term for each decile of the distance distribution. Panel B plots the corresponding effect calculated by multiplying the coefficient by the average distance for firms in each decile.

Figure 16: **Loss Function from Structural Estimation**

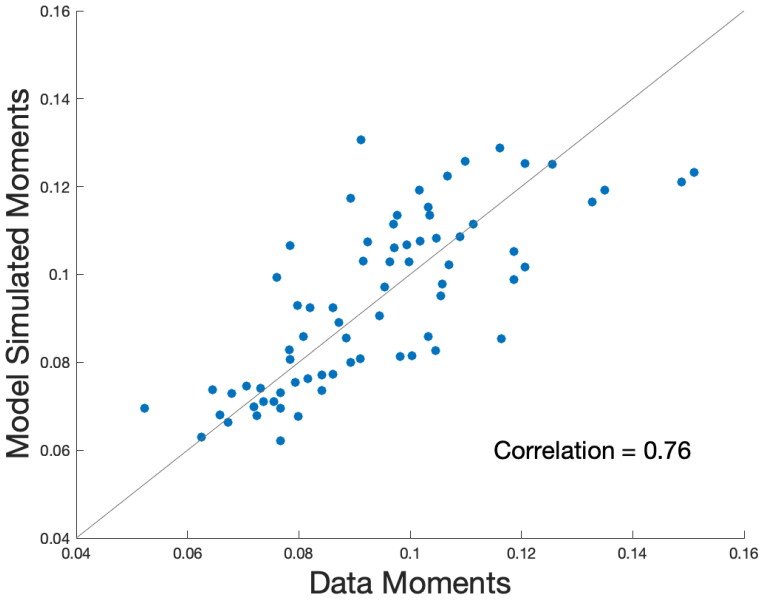


Notes: This graph displays the loss function against each parameter, with the other parameters held at the optimal values. The loss function is calculated by:

$$g(\phi) = [m - \hat{m}(\phi)]' W [m - \hat{m}(\phi)],$$

where the moments m include seven moments regarding firms' geographic expansion and ICT adoption. I use the identity matrix as the weighting matrix. In each panel, the vertical line indicates the estimated value.

Figure 17: **Untargeted Moments: Bilateral Expansion Patterns**



Notes: This figure plots the model-simulated shares of firms that expand from one census division to another against those shares calculated from the National Establishment Time Series (NETS) database. To account for the difference in average expansion shares in the LBD-CNUS matched sample and NETS database, I add a constant to the bilateral expansion shares from NETS.

Table 11: **Matching of the 1999 Longitudinal Business Database and Computer Network Use Supplement**

	Matched Firms		Unmatched Firms	
	N	Mean	N	Mean
Multi-unit firm	4,600	0.466	29,000	0.027
Number of establishments	4,600	3.347	29,000	1.054
Log(employment)	4,600	5.065	29,000	2.548

Notes: This table shows summary statistics for the firms in the 1987–2007 balanced panel of the Longitudinal Business Database (LBD) that are matched to the 1999 Computer Network Use Supplement (CNUS) and for those firms that are not matched. Observations are from the year 1999. Multi-unit firm is an indicator set to one if a firm has more than one establishment.

Table 12: **Summary Statistics of the Balanced Sample from 1987 to 2007**

	N	Mean	S.D.
Employment	702,000	119.10	920.10
Payroll (in thousands)	702,000	4502	47010
Multi-unit firm	702,000	0.084	0.278
Number of establishments	702,000	1.340	2.354

Notes: This table shows summary statistics of the firms in the manufacturing sector from a balanced panel in the Longitudinal Business Database (LBD) from 1987 to 2007. There are twenty-one years during this period. Each firm is a FIRMID×six-digit NAICS industry pair. Multi-unit firm is an indicator set to one if a firm has more than one establishment.

Table 13: **Firms' ICT Adoption, Geographic Expansion, and Communication Patterns**

	Growth Rate from 1997 to 2002 in Number of Establishments		Communication		
	Baseline	Single-Industry Firms	Within-Firm	Customer	Supplier
	(1)	(2)	(3)	(4)	(5)
Intranet	0.030***	0.022**	0.259***	0.105***	0.056***
	(0.010)	(0.009)	(0.009)	(0.009)	(0.009)
Electronic data interchange (EDI)	0.002	-0.012	0.045***	0.092***	0.112***
	(0.011)	(0.008)	(0.009)	(0.009)	(0.009)
Extranet	-0.000	0.019	0.104***	0.159***	0.068***
	(0.018)	(0.020)	(0.012)	(0.014)	(0.012)
Internet	0.012**	0.007*	0.104***	0.129***	0.281***
	(0.006)	(0.004)	(0.006)	(0.007)	(0.008)
Local area network (LAN)	0.009	0.001	0.076***	0.061***	0.148***
	(0.006)	(0.004)	(0.007)	(0.007)	(0.008)
N	16500	13000	18500	18500	18500
Avg. dependent variable	0.047	0.018	0.338	0.294	0.533
R^2	0.025	0.023	0.369	0.227	0.268
Firm controls	Y	Y	Y	Y	Y
Industry FE	Y	Y	Y	Y	Y
State FE	Y	Y	Y	Y	Y

Notes: This table presents the relationship between firms' ICT adoption and their geographic expansion and communication patterns. Columns (1)–(2) use the matched sample from the Longitudinal Business Database (LBD) and the Computer Network Use Supplement (CNUS) and estimate a regression of the form:

$$\Delta Y_{i,97-02} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,97}\gamma + \varepsilon_{i,97-02},$$

where the dependent variable $\Delta Y_{i,97-02}$ is the growth rate of firm i in the number of establishments from 1997 to 2002 ($\Delta Y_{i,97-02} = \log Y_{i,02} - \log Y_{i,97}$). The independent variables include indicators set to one if firm i adopted Intranet, Electronic data interchange (EDI), Extranet, Internet, and Local area network (LAN) by 1999, and $X_{i,97}$ is a vector of the firm's initial characteristics in 1997, including the logarithm of employment, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS level. Column (1) uses firms in the CNUS sample that are matched with the 1997 and 2002 LBD. Column (2) restricts the sample to those firms that operate in a single six-digit NAICS industry throughout the period.

Columns (3)–(5) use the CNUS sample and estimate a regression of the form:

$$Y_{i,99} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,99}\gamma + \varepsilon_{i,99},$$

where the dependent variables are indicators set to one if any establishment of the firm provides information to other company units, external customers, and external suppliers. $X_{i,99}$ is a vector of firm characteristics in 1999, including the logarithm of capital to labor ratio, logarithm of employment, skill mix measured by the ratio of nonproduction workers to production workers, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 14: **Firms' ICT Adoption and Expansion in All Sectors**

	Growth Rate from 1997 to 2002 in		
	Number of Estab's in All Sectors	Employment in All Sectors	%Employment in Mfg.
	(1)	(2)	(3)
Intranet	0.091***	0.168***	0.079
	(0.025)	(0.023)	(0.055)
Electronic data interchange (EDI)	0.047*	0.046**	0.077
	(0.027)	(0.018)	(0.067)
Extranet	0.086*	0.076***	-0.018
	(0.047)	(0.026)	(0.027)
Internet	0.011	0.036**	0.003
	(0.010)	(0.017)	(0.008)
Local area network (LAN)	0.026**	0.128***	0.027
	(0.013)	(0.018)	(0.019)
N	16500	16500	16500
Avg. dependent variable	0.102	0.084	0.019
R^2	0.024	0.062	0.007
Firm controls	Y	Y	Y
Industry FE	Y	Y	Y
State FE	Y	Y	Y

Notes: This table estimates regressions of the form:

$$\Delta Y_{i,97-02} = \alpha + \beta_1 \text{Intranet}_{i,99} + \beta_2 \text{EDI}_{i,99} + \beta_3 \text{Extranet}_{i,99} + \beta_4 \text{Internet}_{i,99} + \beta_5 \text{LAN}_{i,99} + X_{i,97}\gamma + \varepsilon_{i,97-02},$$

where $\Delta Y_{i,97-02}$ is the growth rate of firm i in an outcome Y_i from 1997 to 2002 ($\Delta Y_{i,97-02} = \log Y_{i,02} - \log Y_{i,97}$). The independent variables include indicators set to one if firm i adopted Intranet, Electronic data interchange (EDI), Extranet, Internet, and Local area network (LAN) by 1999. X_i is a vector of the firm's initial characteristics in 1997, including the logarithm of employment, firm age fixed effect, state fixed effect, and industry fixed effect at the four-digit NAICS Level. The dependent variable in column (1) is the five-year growth rate in the number of establishments that firm i has, where we identify a firm by the unique FIRMID and consider the firm's establishments in all sectors. The dependent variables in columns (2) and (3) are the five-year growth rates in the firm's total employment in all sectors and the firm's employment share in the manufacturing sector, respectively. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 15: **Estimates of the Effect of ICT on Firms' Expansion: Intensive Margin**

	Log(Emp) (1)	Log(Emp/Establishment) (2)	Log(Wage) (3)
HQDistToNode × Post	-0.019*	-0.001	-0.004
	(0.011)	(0.011)	(0.004)
N	702000	702000	702000
Avg. Dep. Var	6.123	5.090	3.383
R^2	0.973	0.957	0.837
County Controls	Y	Y	Y
Industry-Year FE	Y	Y	Y
State-Year FE	Y	Y	Y

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variables are the logarithm of employment of firm i in year t, logarithm of employment per establishment, and logarithm of average wage rate of the firm, respectively, for columns (1)–(3). α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, share of the black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The regressions are weighted by the firm's employment share. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 16: **Estimates of the Effect of ICT on Firms' Expansion: Location of New Establishments**

	$\overline{\text{DistToNode}}^{\text{New}}$	$\overline{\text{Log(Pop)}}^{\text{New}}$	$\overline{\text{Log(HH Income)}}^{\text{New}}$	$\overline{\text{\%Poverty}}^{\text{New}}$
	(1)	(2)	(3)	(4)
HQDistToNode × Post	0.315**	-0.318	-0.087***	-0.001
	(0.136)	(0.259)	(0.027)	(0.006)
N	1200	1200	1200	1200
Avg. Dep. Var	1.574	12.36	10.47	0.127
County Controls	Y	Y	Y	Y
Industry-Year FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y
	$\overline{\text{\%Black}}^{\text{New}}$	$\overline{\text{\%Age>65}}^{\text{New}}$	$\overline{\text{\%Bachelor's Degree}}^{\text{New}}$	
	(5)	(6)	(7)	
HQDistToNode × Post	-0.025	0.019***	-0.019	
	(0.016)	(0.005)	(0.012)	
N	1200	1200	1200	
Avg. Dep. Var	0.123	0.125	0.206	
County Controls	Y	Y	Y	
Industry-Year FE	Y	Y	Y	
State-Year FE	Y	Y	Y	

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is a characteristic of the new establishments of firm i in year t, α_i is the firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, shares of the black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. The dependent variable is the average distance from the new establishments to their nearest NSFNET node for column (1). The dependent variable for columns (2)–(7) is the average population, household income, poverty rate, shares of the black population and people over 65 years old, and share of adults with a bachelor's degree of the counties where new establishments are located, respectively. The regressions are weighted by the firm's employment share. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 17: **Estimated Effects of the Internet Privatization on Firms' ICT Adoption**

	Intranet (1)	Internet (2)	Extranet (3)	EDI (4)
HQDistToNode × Post	-0.035***	0.045**	-0.001	-0.020**
	(0.009)	(0.019)	(0.010)	(0.008)
N	58000	58000	58000	58000
Avg. Dep. Var	0.036	0.220	0.009	0.035
County Controls	Y	Y	Y	Y
Industry-Year FE	Y	Y	Y	Y
State-Year FE	Y	Y	Y	Y

Notes: This table estimates regressions of the form:

$$Y_{it} = \alpha_i + \beta \text{HQDistToNode}_i \times \text{Post}_t + \text{CountyControls}_{it}\gamma + \alpha_i^{\text{Industry-Year}} + \alpha_i^{\text{State-Year}} + \varepsilon_{it},$$

where the dependent variable is a time-varying indicator of a firm's network status that interacts the firm's network adoption in 1999 and a postprivatization indicator. The dependent variable in columns (1)–(4) is the firm's adoption of Intranet, Internet, Extranet, and Electronic data interchange (EDI), respectively. α_i is firm fixed effect, HQDistToNode_i is the distance from the ZIP code in which firm i is headquartered to its nearest NSFNET node (in 100 miles), Post_t is an indicator set to one for years after 1995, and $\text{CountyControls}_{it}$ is a vector of county characteristics, including the logarithm of population and median household income, shares of the black population and people over 65 years old, and share of adults with a bachelor's degree. $\alpha_i^{\text{Industry-Year}}$ and $\alpha_i^{\text{State-Year}}$ are industry–year and state–year fixed effects, respectively. Standard errors are clustered at the firm and headquarters county level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 18: **Estimates of Census Division Fixed Effects and the State of Technology in 1999**

	Census Division Fixed Effect		State of Technology
	Raw Estimates	Purified Estimates	
	(1)	(2)	(3)
New England	1.000	1.000	1.000
Middle Atlantic	2.721	1.620	0.985
East North Central	5.948	3.935	1.176
West North Central	2.314	0.695	0.807
South Atlantic	5.613	1.650	0.903
East South Central	2.166	0.536	0.793
West South Central	2.872	1.463	0.971
Mountain	1.537	0.700	0.878
Pacific	4.015	4.322	1.216

Notes: Column (1) reports the 1999 census division fixed effects estimated from the first-stage regression. Column (2) reports the purified fixed effects that are adjusted by the local wage of manufacturers. Column (3) reports the second-stage estimates of the 1999 census divisions' state of technology, i.e., the scale parameter of the Fréchet distribution for each census division. The shape parameter is set to 3.6. The estimated fixed effects and state of technology are normalized to those of the New England census division.

Table 19: **Average Fixed Costs of Setting Up Establishments and Adopting ICT**

Census Division	Average Fixed Costs (in Millions USD)	
	Setting Up Establishments (Establishment Location)	Adopting ICT (Headquarters Location)
New England	2.89	1.35
Middle Atlantic	3.11	1.45
East North Central	2.86	1.44
West North Central	2.37	1.30
South Atlantic	4.57	1.44
East South Central	3.24	1.37
West South Central	3.40	1.35
Mountain	2.77	1.19
Pacific	3.51	1.16

Notes: This table reports the estimated average monetary value of the fixed costs in each census division. Column (1) shows the average costs of setting up establishments in each census division for firms with establishments in multiple census divisions. Column (2) shows the average costs of adopting ICT in the firms' headquarters census divisions for firms that adopt ICT. These costs are calculated with the assumption that the ratio of average sales to the fixed costs from the model is the same as that in data.

Table 20: **Unilateral ICT Cost Reduction: Decomposition of Efficiency Changes**

Census Division	%Change in efficiency	Decomposition (%)				
		Outside Firms				Local
		Stayers	Entrants	Exiters	Never-Comers	Firms
	(1)	(2)	(3)	(4)	(5)	(6)
West South Central	0.052	0	0	-12	0	112
Other Census Divisions	0.024	45	32	-2	25	0
New England	0.020	24	32	0	44	0
Middle Atlantic	0.026	9	83	-2	10	0
East North Central	0.021	87	6	-5	12	-1
West North Central	0.030	58	28	-1	15	-1
South Atlantic	0.017	37	33	-1	31	-0
West South Central	0.024	42	31	-4	31	0
Mountain	0.019	20	29	-5	55	0
Pacific	0.033	83	17	-2	2	0

Notes: This table shows the efficiency gains in each census division with a reduction in the fixed costs of ICT adoption in the West South Central census division and decomposition of this change across the contributions from different types of firms.